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Grain legume production and use in European agricultural systems

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Abstract

There is a great demand for high-protein materials for livestock feed in Europe and European agriculture has a deficit of about 70% high protein materials of which 87% is met by imported soybean and soy meal. This reflects the fact that grain legumes are currently under represented in European agriculture and produced on only 1.5 % of the arable land in Europe compared with 14.5% on a worldwide basis. Several grain legumes have the potential to replace at least some of the soya currently used in the diets of monogastric animals, ruminants and fish. There are also opportunities for greater use of legumes in new foods. Here we review the contribution of ecosystem services by grain legumes in European agriculture starting with provisioning services in terms of food and feed and moving on to the contribution they make to both regulating and supporting services which are in part due to the diversity which these crops bring to cropping systems. We explore the need to understand grain legume production on the time scale of a rotation rather than a cropping season in order to value and manage the agronomic challenges of weed, pests and diseases alongside the maintenance or improvement of soil structure, soil organic matter and nutrient cycling. A review of policy interventions to support grain legumes reveals that until very recently these have failed to make a difference in Europe. We contrast the European picture with the interventions that have allowed the development of grain legume production in both Canada and Australia. Whether farmers choose to grow more legumes will depend on market opportunities, the development of supply chains and policy support as well as technical improvements of grain legume production such as breeding of new varieties and management development to improve yield stability. However, to really increase the production of grain legumes in Europe the issues are far more wide reaching than agronomy or subsidy and require a fundamental rethinking of value chains to move grain legumes from being niche products to mainstream commodities.

Keywords: Ecosystem services, livestock feed, agricultural policy, crop rotations, systems analysis, nitrogen fixation

1 Introduction

Legumes are the second most important family of agricultural crop species after grasses worldwide and are used for both grain and forage, but they are underrepresented in European cropping systems which are dominated by cereals and non-legume oilseeds. This situation has been the subject of public debate in Europe over the last decade and it is now widely acknowledged that grain legumes have the potential to contribute more to European agricultural

systems by improving the agronomic performance of cropping systems and providing protein-rich food and feed and helping to reduce European dependence on imported protein. Grain legume production contributes widely to ecosystem services by its low reliance on synthetic fertilizers; reduced greenhouse gas emissions; increased diversification of the crop rotation with concomitant increases in above- and below-ground biodiversity and changes in weed, pest and disease pressures; and changes in soil fertility and carbon storage. This combination of ecosystem services (Millennium Ecosystem Assessment, 2005) related to legume production provides internal (market and non-market) and external effects and raises a number of questions for value chain developers: what are the effects of legume production for farmers; what are the innovation challenges; and how can changes in European farming systems be achieved. This review examines these questions in the context of the sustainable development of Europe's agricultural and food systems, and takes a systems view as ultimately, the developments we are considering all depend on the decisions made by Europe's farmers who depend on production options, market developments and policies that altogether influence their decisions. We use the term "grain legume" in its broadest sense, to indicate a legume of which the seed is the main harvested component, thus including the oilseeds soybean and groundnut, and we follow the FAO in restricting the term "pulse" to the starchy legumes and lupins, excluding the oilseeds.

2 The changing role of legumes in European agriculture

The use of legumes in cropping has effects that range from the field to the global scale. The global impacts are particularly relevant in Europe as a driver of efforts to restore the use of legumes. Grain legumes were grown on 14.5% of the global arable cropped area in 2014, accounting for 12.5% of the production of all grain crop produce (cereals, pulses and oilseeds) (FAOstat, 2016), but in the EU the corresponding figure is only 1.5% of the arable area, dominated by soybean, pea and faba bean in that order (Eurostat, 2016). Therefore, the role of grain legumes in European cropping systems is about 10% of their average role in cropping systems world-wide.

This low level of grain legume production is the result of a long-term trend over at least five decades. During this period, the EU28 achieved remarkably high levels of self-sufficiency in key agricultural commodities. It is now more than 100% self-sufficient in the major meats (pigmeat, poultry, beef), milk, and cereals (FAOstat, 2016). This means the EU is a net exporter in of these commodities. Using data from FAOstat, we estimate that the total consumption of protein derived from tradable arable crop products (import + EU production - export) was 55 million tonnes (M t) in 2011, of which 52% is provided from cereal grains. About 60% of this cereal protein is fed to animals to support these high levels of self-sufficiency in livestock products. In addition, forage

maize provided 3.9 M t of protein, almost all for beef and milk production. When all supplies and trade are considered, the EU is 69% self-sufficient in tradeable plant protein. Nevertheless, high-protein crop commodities, mostly from oilseed residues and pulses, are an essential component of cereal-based compound feeds, and are in deficit by 71%, of which 87% is met by imported soybean and soy meal. These data confirm other assessments based on industry data that the EU deficit in high-protein materials is around 70% (Houdijk et al., 2013; Bouxin, 2014). Thus, European agriculture can be characterised as reliant on a combination of reactive N in fertilizers and in imported feeds, allowing arable land to be allocated to high-yielding cereals and oilseeds (especially oilseed rape). A number of forces have come together since 1960 to result in this situation: changes in trade policy; technical change in livestock production; and economic growth leading to increased disposable income that in turn leads to increased demand for meat and dairy products (Billen et al., 2012; Lassaletta et al., 2014). Between 1961 and 2011, livestock production in Europe increased in line with consumption that rose from the equivalent of 822 kcal/capita/day to 993 kcal/capita/day with 395 and 170% increases in poultry and pigmeat respectively (FAOstat, 2016; Figure 1). This was facilitated by intensification in production, particularly for pigs and poultry, associated with a decoupling of livestock production from the land resource base used to provide feed. Changes in trade policy gave European farmers access to low-cost soybean and soy meal. Increases in soy imports align with increases in livestock production, particularly pigs and poultry (Figure 1). The current level of livestock production, based largely on European-grown cereals, is facilitated by the complementary qualities of soybean meal, especially with regard to amino acid profiles. The European ban on animal protein supplements in livestock diets, introduced in the 1990s to prevent the spread of Bovine Spongiform Encephalopathy (BSE) and to the development of similar diseases, increased the use of soybean in livestock diets (Vicenti et al., 2009) causing a sharp increase in soybean imports in the second half of that decade (Figure 1).

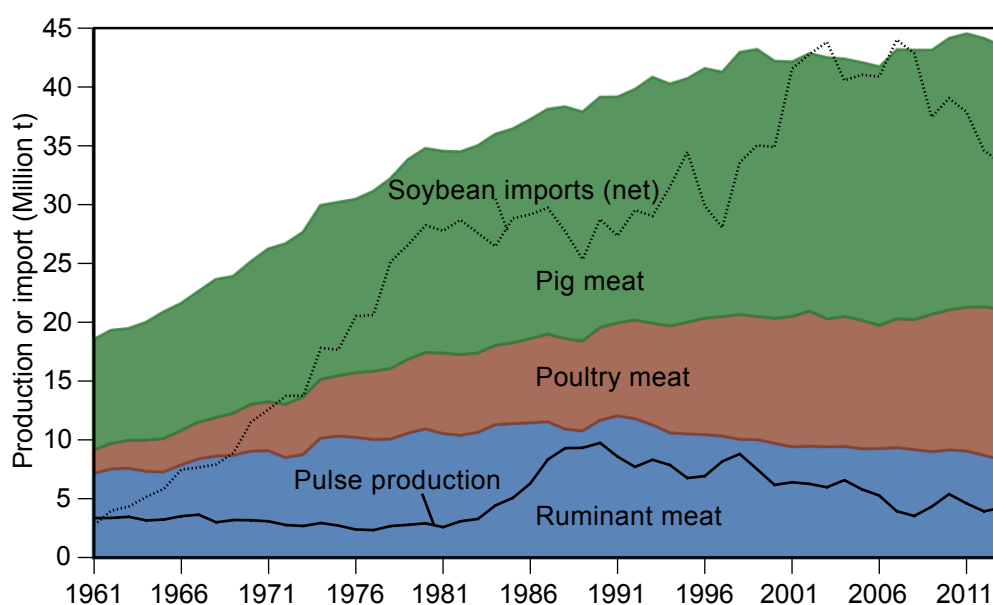


Figure 1: Changes in the production of meat and legumes, along with import of soy, in the EU-27 countries from 1961 to 2013. Ruminant meat was 87-90% cattle meat, depending on the year, with the remainder sheep, goat and buffalo. Poultry meat was 89-91% chicken in the first 5 years, declining to 80-82% chicken in the last 5 years. For the soybean net imports (dotted line), soybean meal was converted to bean equivalents assuming 79.2% meal content (US Soybean Export Council 2016), and exports were subtracted. Pulse data (solid line) include pea, faba bean, lupins, common bean, chickpea, lentil, cowpea, and "other pulses" (mostly UK-grown faba bean). All data from FAOstat 2016.

3 Provisioning Services from grain legumes in European agricultural systems

Agricultural products, in the context of the ecosystem services concept, are seen as provisioning services to human society. Grain legumes play a major role in this by providing proteins for food and feed products. In the next sections we describe the major benefits / processes / functions obtained from cultivation of grain legumes

3.1 Food

Grain legume seeds contain protein, soluble and insoluble fibre, slowly digested starch, micro- and macro-nutrients, vitamins and numerous bioactive phytochemicals, such as flavonoids and other antioxidants (Bassett et al. 2010; Scalbert et al., 2005; Strohle et al., 2006). The amino acid profile of grain legume protein complements that in cereals. Grain legumes have played an important role in human diets for thousands of years. Grain legumes contain 20 – 45% protein compared with 7 – 17% in cereals (Day 2013). The protein content ranges from 20 – 25% in common bean (*Phaseolus vulgaris* L.), lentil (*Lens culinaris* Medik.) and pea, to over 40% in soybean and yellow lupin (*L. luteus* L.). Plant products based on soybean can reduce risks to cardiovascular health (Sirtori et al., 2009) through lowering cholesterol and controlling hypertension (Harland and Haffner, 2008). Consumption of soybean and lupin products has been shown to reduce cholesterol in humans (Sirtori et al., 2012), and grain legumes may also be useful in the diet of diabetics (Bertoglio et al., 2011), although the mechanisms of these effects remain to be elucidated (Arnoldi et al., 2015). Some of the bioactive components, such as tannins and phytate, affect palatability, digestibility and nutrient availability. Many, such as phytohaemagglutinin of common bean and trypsin inhibitors of most species, are substantially or completely denatured by cooking. Others, such as phytate (myoinositol hexakisphosphate) and raffinose series oligosaccharides, can be degraded by endogenous enzymes during germination or by exogenous enzymes in a food matrix. Still others, such as vicine and convicine in faba bean, require a breeding solution. The main legume storage proteins are globulins, defined by their solubility in saline solution, and are easily extracted for use in dairy analogue products.

Further technological input, such as the pressure-heat treatment in extrusion, allows textured vegetable protein to be produced to emulate meat on the plate and in the mouth. Soybean-based milk and textured protein products are familiar in many countries, and adaptations to the technology are under investigation so that other crops, such as narrow-leafed lupin or faba bean, can be used (Jiang et al., 2016; Stephany et al., 2016).

Davis *et al.* (2010) used LCA (life cycle assessment) to examine the full spectrum of environmental effects of introducing more grain legumes in human nutrition. Replacing meat by peas led to a reduction of global warming, eutrophication, acidification, and land use, but a completely vegetarian pea burger meal required the same amount of energy input as the meat-containing meals, due to intensive processing.

3.2 Feeding cattle and sheep

Grain legumes can be utilized flexibly in diets of all ruminant species either in concentrate compound feed or as whole crop forage. Unlike monogastrics, ruminants are not susceptible to most of the antinutritional factors of grain legumes owing to the microbial fermentation taking place in their forestomachs (Dixon and Hosking, 1992). LCA studies show advantages of replacing soybean by European legumes in ruminant feed. Using locally produced pea and oilseed rape (*Brassica napus* L. ssp. *oleifera* Metzg.) to replace soybean resulted in a 15% reduction in the GHG carbon footprint of milk (Sasu-Boakye et al., 2014). Similarly, Baumgartner et al. (2008) found lower adverse environmental impacts for replacing soybean meal by European legumes for feeding dairy cows, with the exception of eutrophication. The feasibility of the use of grain legumes in ruminant diets is determined not only by their chemical composition and how they complement the forage component of the diet, but also by the rate and extent of degradation of nutrients in the rumen. The degradability of grain legume protein in the rumen is often over 80%, similar to that of most cereal grains (Dixon and Hosking, 1992; Luke, 2016). Using methods such as heat treatment to improve availability of protein to the animal have seldom been successful in terms of added value for milk production as shown for pea (Petit et al., 1997), narrow-leafed lupin (White et al., 2007) and faba bean (Ramin et al., 2015). This may be attributed to the suboptimal amino acid profile in undegraded grain legume protein, which is especially low in the limiting amino acids such as methionine (White et al., 2007; Van der Pol et al., 2008; Puhakka et al., 2016). This suggests that supplemental amino acids may be necessary when grain legumes are fed to high-producing dairy cows. Pea and faba bean starches have lower degradability in the rumen than cereal starches (Larsen et al., 2009) and lupins have higher metabolizable energy content (White et al., 2007) than cereal grains, which may contribute to the supply of metabolizable energy to the ruminant animal and explain why replacement of cereal grains with grain legumes in dairy cow rations often increases milk

production (Dixon and Hosking 1992, White et al., 2004, White et al., 2007, Puhakka et al., 2014), but not always (Khalili et al., 2002).

As soybean meal (SBM) is usually considered the standard supplementary plant protein source in animal feeds, most studies examining the effects on protein sources on livestock production use isonitrogenous comparisons, with SBM used as the control. This type of research shows for example that SBM can be completely (Petit et al., 1997, Khorasani et al., 2001) or partly (Van der Pol et al., 2008) substituted by pea as the protein source in various stages of lactation of cows without any adverse effect on milk production. The same was shown for substituting SBM by faba bean (Ingalls and McKirdy, 1974, Tufarelli et al., 2012), white lupin (Froidmont and Bartiaux-Thill, 2004) or narrow-leaved lupin (White et al., 2007), with the exception of some studies showing reduced milk protein concentrations.

Rapeseed meal (RSM) is another tradeable protein source that can be partially substituted by grain legumes. Meta-analyses show that most feed evaluation systems overestimate metabolizable protein concentration of SBM relative to rapeseed meal (Huhtanen et al., 2011). Replacement of RSM with pea impaired milk production, but a combination of pea and RSM resulted in similar performance to that of RSM alone (Khalili et al., 2002). In an early study, no difference was found in milk production parameters between faba bean and RSM (Ingalls and McKirdy, 1974), but a recent comparison showed lower milk yields from the use of faba bean (Puhakka et al., 2016). The replacement of a portion of protected RSM with narrow-leaved lupin reduced milk protein concentrations of pasture-fed cows (White et al., 2004). Variation in dairy cow production responses to grain legume supplementation may be attributed to the various types of forages used in the experiments, as well as to variable effects of grain legumes on dietary dry matter intake (Puhakka et al., 2016). Grain legume – cereal crop mixtures for silage production have proved beneficial in dairy cow feeding (Adesogan et al., 2004; Pursiainen and Tuori, 2006). These effects arise from the energy and protein complementarity of the components providing an appropriate balance between readily fermentable nutrients for microbial protein synthesis in the rumen. Furthermore, mixing grain legume-cereal whole-crop silage with grass-clover (Rondahl et al., 2007) or grass (Lamminen et al., 2015) silages may maintain or increase intake and milk production of dairy cows in comparison to conventional grass-based forage rations.

3.3 Feeding pigs and poultry

SBM accounts for 84% of all the high-protein oilseed meal used in compounded livestock rations worldwide (FAOstat 2016). There are no official data on the use of soy in the various livestock sectors, but Gelder et al. (2008) estimated the allocation of the Dutch-consumed soy to livestock species based on feed formulation and farm practice in the Netherlands, with inclusion rates in

concentrate feed of 37%, 29%, 22% in feeds for broilers, pigs and laying hens, respectively. The inclusion of soy in beef and dairy concentrate feeds was lower at 14% and 10% respectively. This results in the following rates of use on a per unit food commodity output basis: beef, 232 g/kg; milk, 21 g/kg; pork, 648 g/kg; poultry meat, 967 g/kg; eggs, 32 g/egg. These estimates indicate that monogastrics (pigs and poultry) account for at least 80% of soybean meal use in the Netherlands. Hoste and Bolhuis (2010) reported slightly different rates of use of soybean meal as follows: 100 g/kg veal produced, 600 g/kg of poultry, 11 g/kg of raw milk and 330 g/kg of eggs. The total industrial feed production in Europe was 155 million tonnes in 2013 (FEFAC, 2014). Our assessment of the FEFAC data agrees with that of Westhoek et al. (2011) that inclusion rates of soy in feed are lower across the EU than suggested by Gelder et al. (2008) for the Netherlands. Nevertheless, it is clear that the increase in the production of monogastric meats is the primary driver behind the increases in the demand for soybean over the last fifty years.

SBM is the standard protein supplement in pig feed (Crépon, 2006; Jezierny et al., 2010) due to its high crude protein (CP) content (44 %) and useful amino acid profile, unmatched by other grain legumes that are deficient in the essential amino acids methionine, cysteine and tryptophan (Gatel, 1994). The use of legumes in monogastric diets is constrained by the presence of anti-nutritional factors including non-starch polysaccharides (NSP), tannins, phytate, saponins and trypsin inhibitors that have adverse effects on nutrient digestibility and absorption (Gatel, 1994) and can result in reduced feed intake, reduced digestibility or even toxicity (e.g. Huisman and Jansman, 1991). In the past, both reduced pig growth (Crépon, 2006) and increased boar taint indicators (Madsen et al., 1990) have been associated with diets high in pea and faba bean. However, White et al. (2015) and Smith et al. (2013) demonstrated that peas and beans can be used in balanced pig diets without any negative effects on production compared to soybean meal. Research on the use of legumes in both pig and poultry diets shows that processing may be important in allowing greater proportions of grain legumes to be used, for example, increases in starch digestibility as a result of dehulling faba beans have been shown (Nalle et al., 2010). Other effective treatments include dehulling to reduce tannin and fibre content, heat treatments such as extrusion or toasting to denature heat-labile anti-nutritional factors, particle size reduction to increase digestibility through increased surface area, and fractionation to select components rich in nutrients (Woyengo et al., 2014). Fibre-degrading enzymes can be added in order to increase dietary nutrient availability, or diets can be formulated according to the bioavailability of essential amino acids. Pea, faba bean and lupins have all been shown to be suitable as partial substitutes for soybean in broiler diets, although lupins are the least effective because of their high content of indigestible cell walls (Diaz et al., 2006) and faba bean needs to have a low vicine-convicine content (Crépon et al., 2010). These alternatives to soybean have also been shown to be acceptable in egg production (e.g. Laudadio and Tufarelli, 2010).

Studies using LCA have shown that the main effects of replacing imported soybean with European grain legumes are reduced transport distances, avoided deforestation impacts and rotational benefits. Since soybean is also a legume, the advantages of BNF are present in both systems. Other effects on acidification, energy use, eutrophication, global warming potential, land use, ozone formation and toxicity depend strongly on the basis of comparison, as shown below. Since pea and faba bean are starchy, their use in feed affects the starch cereal component as well as the protein-rich soybean component that they are intended to replace, adding to the complication of the analysis. Production methods, yield levels (Nemecek et al., 2012), and cultivar (Abeliotis et al., 2013) all affect the environmental impact of the legume crop compared with alternatives. Until 2006, LCA studies used the same 1% N₂O emission factor for biologically fixed N as for mineral and manure fertilizers, but since then IPCC methodology has set the emission factor for biologically fixed N used by the legume to zero (IPCC, 2006). Schwenke et al. (2015) determined that 75% of a legume crop's N₂O emission took place after harvest.

Eriksson et al. (2005) compared three scenarios for pig feed formulations: a standard formula with soybean meal, domestic feed (no soybean meal) with a low crude protein level and added synthetic amino acids, and organically produced feed. The first scenario had the lowest environmental impacts for land use, the second for acidification and eutrophication, and the third for energy use and global warming potential. With the exception of eutrophication, conventional (Dourmad et al., 2014, Garcia-Launay et al., 2014) and organic soybean (Dourmad et al., 2014) from Brazil had greater environmental burdens than pea grown in Europe. On a global scale, GHG emissions from soybean and pea per kg were similar when land-use change impacts were taken into account. Garcia-Launay et al. (2014) showed that replacing part of the soybean in the pig rations with rapeseed meal, pea and synthetic amino acids reduced environmental impacts.

Van der Werf et al. (2005) showed that pea resulted in higher impacts than wheat or barley for eutrophication, energy use and climate change. Similarly, Nguyen *et al.* (2012) found that impact reduction was obtained by partial substitution of soybean meal and cereals in poultry feed with rapeseed meal, grain legumes and cereal co-products (wheat bran, gluten). Baumgartner et al. (2008) found that the main effect of introducing European grain legumes to replace soybean were found in reduced energy demand, reduced greenhouse gas emissions, and reduced ozone formation. Producing the feedstuffs on-farm further reduced the environmental burden. No clear tendency was observed for eutrophication and acidification, while the toxicity tended to be higher for the European legumes because of differences in pesticide use. Effects were determined more by the composition of the whole feed formulas than by the replacement of soybean meal by peas and beans alone.

Reckmann *et al.* (2016) assessed three alternative diets with reduced inclusion of soy for gestating and lactating sows as well as growing and finishing pigs, reducing the soy component by (a) using a combination of different feedstuffs (e.g. rapeseed meal, faba bean, and synthetic amino acids), (b) maximising the use of legumes (mainly faba bean), and (c) increasing the amount of synthetic amino acids. These alternative diets were formulated to reduce the crude-protein content of the diet while maintaining animal productivity. Per kg of feed, the standard diets was best with regard to global warming, eutrophication, and acidification, and both the standard and amino acid-fortified diets had low impacts on emissions from land use and land-use change. Per kg of pork, however, the amino acid-fortified diet contributed the least in all impact categories, while the legume-maximizing scenario had higher impacts than the standard diet for global warming and land use.

Thus LCA does not show any strategy for monogastric feed production to be a universal panacea, as it demonstrates that benefits in one area such as land-use change are countered by detrimental effects in another area.

3.4 Feeding fish

Legume-based products can replace or reduce the need for fish meal for feeding many farmed fish and crustaceans (Trushenski *et al.*, 2006). The potential of a range of plant-based protein sources for fish feed was reviewed by Ayadi *et al.* (2012). Compounded fish feeds contained a mean of 25% soybean meal in 2008, representing 4.5% of world soybean meal production in that year, and use of other pulse and cereal proteins is increasing (Tacon *et al.*, 2011). Herbivorous fish such as carp (*Cyprinus carpio* L.) can by definition be raised exclusively on plant-based feeds. Faba bean and pea have been shown to be the most suitable grain legumes for inclusion in diets for Atlantic salmon (*Salmo salar* L.) (Aslaksen *et al.*, 2007). White lupin (*L. albus* L.) and pea were equally good for rainbow trout (*Oncorhynchus mykiss* Walbaum) (Zhang *et al.*, 2012). Narrow-leaved lupin meal can be used at up to 30% of the diet of rainbow trout (Glencross *et al.*, 2008) and the protein concentrates from this species are efficiently converted by the fish (Zhang *et al.*, 2012). Similarly, Pacific white shrimp (*Litopenaeus vannamei* Boone) grew well with up to 50% of the protein in the feed being plant-derived (from Andean lupin, *L. mutabilis* Sweet) (Molina-Poveda *et al.*, 2013). The presence of some starch helps the formation of feed pellets under heat extrusion, so faba bean or pea flour can replace some of the wheat or other cereal starch in the formulation.

As with pigs and poultry, there is a need to account for the anti-nutritional factors present in grain legumes. For example, saponins are known to reduce growth in salmonids (e.g. Krogdahl *et al.*, 2015), and faba bean is better in this regard as it contains around 4.3 g kg⁻¹ of saponins compared to 43 g kg⁻¹ in soybean (Fenwick and Oakenfull, 1983).

4 Supporting and regulating services from grain legumes

Besides their direct use in food and feed, legumes offer supporting services in production of subsequent crops and regulating services that are not marketable in conventional settings. Supporting services include biological nitrogen fixation and other rotational effects, and regulating services include positive externalities of legumes related to nutrient management, greenhouse gas impacts of agriculture and biodiversity conservation. These are outlined in the following sections.

4.1 Exploiting biological nitrogen fixation (BNF)

The capacity of legumes, in conjunction with rhizobium symbionts, to fix atmospheric nitrogen is one of the key features distinguishing them from other arable crops. The amount of nitrogen fixed by legumes depends not only on species and cultivar but also on environmental factors such as temperature, water availability (see examples for pea and faba bean grown as sole crops, Table 1), and the availability of mineral N. Grain legumes in Europe were calculated to fix an average of 133 kg ha⁻¹ totalling 225 Gg of N in 2009 (Baddeley et al., 2013). The three major contributors were faba bean, pea, and soybean in that order, with 10-fold less N fixed by (in order) lupin, vetch, common bean, lentil, and chickpea (Baddeley et al., 2013). The values for soybean and common bean were lower than might be expected from their areas, on account of their low published Ndfa values.

Differences among the rhizobium strains in the root nodules influence the BNF capacity of the crop, depending on their compatibility with the host and their competitiveness for nodulation. The relationship between the symbiotic partners is very complex and consists of interactions at many levels (for reviews see Franche et al., 2009; Lindström and Mousavi, 2010). Inoculants comprising effective, nitrogen-fixing bacteria are commercially available, often selected for regional or national adaptation. Since nodulation properties depend on both host and rhizobium, it is recommended that inoculants should be used to ensure good nodulation and BNF in newly introduced crops. Even if there are naturalized rhizobia in the soil, inoculation can optimize BNF and increase crop yield (Denton et al., 2013). The inoculants are selected for high rates of BNF and for competitiveness in field conditions (Yates et al., 2011). Genetic determinants in rhizobia contributing to host-specificity of nodulation are fairly well known. Determinants contributing to effectiveness of BNF are still to be unravelled, but Österman et al. (2015) detected bacterial genes associated with good effectiveness in the forage legume, goat's rue (*Galega orientalis*

Lam.). Breeding for enhanced BNF has been reported for crop legumes (Herridge and Rose, 2000), but no commercial success stories have been reported due to the complex nature of this trait.

An inverse relationship between fixation rate and available mineral nitrogen is widely accepted (Salvagiotti et al., 2008). Many agronomists and farmers advocate the use of "starter" nitrogen fertilizer at 20-40 kg ha⁻¹, to allow the crop to establish while the nitrogen-fixing symbiosis initiates. When available mineral N in the soil was less than this amount, there was a benefit to final yield in many experiments on pea in Canada (McKenzie et al., 2001). Similarly, 8-24 kg ha⁻¹ of starter N assisted soybean establishment in cool soils in the USA, with little effect on subsequent Ndfa (Osborne and Riedell, 2011). Thus there seems to be little reason to reject the use of starter nitrogen for grain legume crops.

Table 1 Variation in N fixation and Ndfa with species, cultivar and European country as sole crops and for pea intercropped with spring barley

Legume	Cultivar	Country	Sole crop		Intercrop with spring barley ^a		Method ^b	Reference
			N fixed (kg/ha)	pNdfa (%)	N fixed (kg/ha)	pNdfa (%)		
Pea	Baccara	FR	110-204	47-77	71-209	58-91	NA	Corre-Hellou et al. (2006)
Pea	Agadir	DK	150	62-72	90	73-87	ID	Hauggaard-Nielsen et al. (2008)
Pea	Baccara	DK, UK, IT, FR, DE	61-154	47-81	32-78	52-84	ID	Hauggaard-Nielsen et al. (2009)
Pea	Bohatyr	DK	140	76	65	86	ID	Andersen et al. (2004)
Pea	Bodil	DK	128-215	53-68	27-74	79-84	ID	Jensen (1996)
Pea	Focus	DK	120	89	30	95	ID	Hauggaard-Nielsen et al. (2001)
Pea	Baccara	FR	238 ^c	84			ID	Voisin et al. (2002)
Pea	Ballet	PT	27-55	29-74 ^d			ID	Carranca et al. (1999)
Pea	Nitouche	FR	96-102 ^c	60-65			ID	Corre-Hellou and Crozat (2005)
Pea	Lucy	FR	173-218	71-82			NA	Naudin et al. (2010)
Faba bean	16 genotypes	FR	34-253	40-83			NA	Duc et al. (1988)
Faba bean	Favel	PT	73-79	69-73a			ID	Carranca et al. (1999)
Faba bean	Columbo	DK	160-170	70-75			ID	Hauggaard-Nielsen et al. (2008)
Lupin, NL	Prima	DK	140-150	76			ID	Hauggaard-Nielsen et al. (2008)
Lupin, white	Multitalia	IT	178 ^c	76			ID	Sulas et al (2016)
Chickpea	Cutivar 510	PT	23	81 ^d			ID	Carranca et al. (1999)
Soybean	3 varieties	DE	43-100	43-55			NA	Zimmer et al. (2015)
Soybean	Maple Arrow	CH	25 ^c	41-47			NA	Oberson et al. (2007)
Soybean	Apache	AT		40-52			NA	Schweiger et al. (2012)

^a All studies used the replacement design, each species being sown at half its sole crop density; ^b Method to determine N fixation (NA, natural abundance and ID isotope dilution); ^c N fixed was measured in shoots plus roots; ^d pNdfa in pods

While the total amount of N fixed is generally higher in grain legumes grown as sole crops than in intercrops, the proportion of N derived from fixation (%Ndfa) is higher in intercrops, as the cereal takes up any mineral N in the soil, forcing the legume to rely on BNF (Bedoussac et al., 2015). This is shown in a range of pea – barley mixtures in different countries (Table 1) as well as in other mixtures such as pea – wheat (Ghaley et al., 2005). N fixation is affected by the frequency of legumes in the rotation, with continuous pea cropping reducing the proportion of N derived from the atmosphere to 15% compared with an average of 55% in peas grown every second, third or fourth year, but the mechanisms for this remain unclear (Knight, 2012).

Phosphorus, potassium and sulphur deficiencies affect BNF directly by affecting plant growth and indirectly by a series of mechanisms including nodule growth and activity (Divito and Sadras, 2014). Other stresses reducing BNF include sub- or supra-optimal soil pH (Vargas and Graham 1988), toxic elements (Obbard and Jones, 2001; Fox et al., 2007), some agrochemicals including organochlorine pesticides (Fox et al., 2007), pest or pathogen attack (Corre-Hellou and Crozat, 2005), and low availability of micronutrients (particularly boron and molybdenum) (O'Hara et al., 1988; Brodrick et al., 1992; Carpena et al., 2000). Positive interaction with arbuscular mycorrhizal fungi have been postulated, but has proven hard to validate in the field (Chalk et al., 2006).

4.2 Outputs through effects on rotations

Introducing legumes into cropping systems often positively affects the nutrient status, organic matter, soil structure, and disease inoculum levels in the soil increasing subsequent crop yields. These are therefore internal effects resulting indirectly in market outputs, i.e., the increased yields in subsequent crops. In practice, this is due to a combination of 'break-crop' and 'nitrogen' effects (Chalk, 1998). The nitrogen effect comprises the provision of N to the subsequent crops. The break-crop effect occurs when rotations that lack crop diversity, as are found in many cereal production systems in Europe, are 'broken' by a broad-leaved crop or a rotational grass-clover ley (Robson et al., 2002). The components of the break-crop effect include reductions in weeds, pests and diseases (Prew and Dyke, 1979; Stevenson and van Kessel, 1997) and improvements in soil structure (Chan and Heenan, 1996). Legume-specific break-crop effects include changes in soil microbiology, particularly the enhancement of growth of some beneficial soil micro-organisms (Crews and Peoples, 2004; Maimaiti et al., 2007; Peoples et al., 2009). One of the mechanisms involved is that hydrogen gas, a by-product of BNF, supports the growth of hydrogen-utilising bacteria in the rhizosphere of the legume nodule, which in turn supports populations of soil fauna (La Favre and Focht, 1983) and of plant growth-promoting rhizosphere bacteria (Dong et al. 2003; Lugtenberg and Kamilova, 2009; Golding and Dong, 2010). The root growth of many crops is better following legumes than after non-legumes, for example, the root

density of broccoli in the subsoil was significantly higher following narrow-leaved lupin than after winter oilseed rape (Thorup-Kristensen, 1993), but it is unclear how this effect is partitioned among changes in the soil microbial environment, soil structure and nutrient availability. The origin of the term 'break-crop effect' is attributed to the breaking of the cycles of soil-borne root diseases such as take-all root rot (*Gaeumannomyces graminis* (Sacc.) Arx & D.L. Olivier) of cereals that die within a year in the absence of a suitable host. Similarly, root-lesion nematodes (*Pratylenchus* spp.) infest many crops, but some cultivars of faba bean suppress the growth of *P. neglectus* (Rensch) Filipjev and Schuumans Stekhoven, reducing the infestation of the subsequent crop (Yunusa and Rashid, 2007). These improvements of the root health of following crops are often most easily detected in their improved N nutrition, although the effect is not one of N provision (Kirkegaard et al., 2008). The impact on the following crop is to some extent soil-type dependent, as the N in root-zone residues can significantly promote root growth in sandy soil but not detectably in loamy soil (Jensen et al., 2004).

The precrop effect is generally described in terms of nitrogen, but the residues of grain legumes can also influence phosphorus availability to the following crop. Grain legume roots exude a range of carboxylates that solubilize phosphate from insoluble forms including calcium and iron salts that are immobile in the soil and generally considered unavailable to plants. The quantity of carboxylates released depends on the concentration of plant-available phosphorus in the soil, with low levels promoting greater release. The number and type of carboxylates depend on the species, with faba bean releasing only malic and citric acids whereas some lupins release up to eight acids (Egle et al., 2003). Phosphorus uptake ability ranged 3-fold among 50 faba bean accessions in a germplasm survey, and in a pot test, the difference in release of soil phosphate was detectable in the following wheat sown immediately after the beans were harvested (Rose et al., 2010).

In a survey, farmers estimated that wheat grown after grain legumes produced 0.6 t ha⁻¹ more yield than when grown after cereals in Belgium, central Spain and Switzerland, and 0.9 t ha⁻¹ in Germany and northern Spain (von Richthofen et al., 2006a). In a meta-analysis including 300 comparisons, wheat grain yields were 1.2 t ha⁻¹ greater after legumes than after wheat (Angus et al. 2015). Estimates of the effects on the optimum nitrogen fertilizer requirements of following crops, based on expert estimations, observations of farmer practice, models and additional crop N take-up in experiments, averaged 23–31 kg/ha (Preissel et al., 2015). These values are much lower than estimates of the residual N of legumes, which can be explained by the larger N demand of high yielding subsequent crops.

The size of the nitrogen-related yield effect to the following cereal depends on the species of the legume crop, with high-biomass crops such as faba bean generally leaving more residue giving a

greater effect than low-biomass crops such as chickpea (Table 4). The pre-crop effect on yield further depends on the amount of N fertilizer used as well as on the species of the pre-crop and the site (Table 2; see also Preissel et al., 2015 for a meta-analysis on an overlapping data set). Unfertilized cereals gained 1-3 t ha⁻¹ in experiments in Denmark, Switzerland, Austria, Germany and the UK. With increasing fertilization, the importance of the legume's nitrogen residue diminishes and the yield effects become more heterogeneous, as shown by comparing results from experiments located near each other in the UK or in Switzerland and Bavaria (Table 4). High yield gains in other highly fertilized trials show the importance of non-nitrogen effects of the legume pre-crop and in absolute numbers most of the yield gain often remains at high N doses (Engström and Lindén, 1999). Other crops besides cereals, such as oilseed rape and potato (*Solanum tuberosum* L.), also show growth responses to grain legume pre-crops (Jensen and Haahr, 1990; Charles and Vuilloud, 2001) as long as broad-spectrum pathogens such as *Sclerotinia sclerotiorum* (Lib.) de Bary and *Rhizoctonia solani* Kühn are controlled in the rotation.

Under optimal fertilization and with full pest and disease management, grain legumes are not a consistently better pre-crop for wheat or barley than other broad-leaved crops or, in some situations, oat (Preissel et al., 2015). While it is difficult to calculate the value of legumes in rotations to crop yield at a large scale, Brisson et al. (2010) suggested that the reduction in the area of legume cultivation in France, resulting from policy and economic changes along with the difficulty of managing root rot diseases of pea, could be part of the reason for the stagnation of cereal yields.

Yield gains of 0.2-1.0 t/ha were typically found in cereals after grain legumes in experiments under Mediterranean conditions in Spain, Italy and Cyprus, regardless of the fertilization level (Table 4; Preissel et al., 2015). In 72 site-years of data from Spain (Preissel et al., 2015), results were mixed partly in favour of the legume (especially faba bean and vetch) and partly in favour of fallow (especially compared to chickpea), with a median difference of 160 kg/ha in favour of fallow (López-Bellido et al., 1998; López-Bellido et al., 2001; López-Bellido and López-Bellido, 2001; Melero et al., 2011; Soldevilla-Martinez et al., 2013).

A pre-crop effect also applies to the legume which can be affected by the preceding crop. The mineral nutrient uptake of faba bean and narrow-leaved lupin was influenced by the preceding crop, with oat and, barley, and turnip rape (in the case of lupin) resulting in increased nutrient uptake and grain yield in the legume compared with pre-crops of wheat, rye or other grain legumes (Lizarazo et al., 2015).

Table 2: Yield effects of grain legumes and oilseed rape as pre-crops on subsequent cereals, classified by nitrogen fertilizer rate. The yield effect is the difference (kg ha⁻¹) or percentage

increase of the yield of the subsequent crop following the break crop compared to the yield of the same crop, usually following the same cereal.

Pre-crop	Crop	N rate (kg ha ⁻¹)	Yield effect (%)	Yield effect (kg ha ⁻¹)	Country	Source
No fertilization (0 kg N ha⁻¹)						
Pea	Wheat	0	114%	3109	DE, Thuringia	Albrecht and Guddat (2004)
	Wheat	0	135%	2700	UK, Rothamsted	McEwen et al. (1989)
Faba bean	Wheat	0	104%	2759	DE, Thuringia	Albrecht and Guddat (2004)
	Wheat	0	156%	3125	UK, Rothamsted	McEwen et al. (1989)
	Barley	0	75%	1248	UK, Rothamsted	Dyke and Slope (1978)
	Oats	0	27%	920	DE	Justus and Köpke (1995)
	Wheat	0	36%	1092	ES, Andalucia	Melero et al. (2011)
	Wheat	0	100%	1750	DE, Thuringia	Albrecht and Guddat (2004)
Narrow-leafed lupin	Wheat	0	100%	1750	DE, Thuringia	Albrecht and Guddat (2004)
Oilseed rape	Wheat	0	11%	434	AT, Lower	Dachler and Köchl (2003)
Moderate fertilization (20-90 kg N ha⁻¹)						
Pea	Wheat	77	24%	1267	DE, Bavaria	Panse et al. (1994)
	Rye	45-80	6%	550	CH	Charles and Vuilloud (2001)
Faba bean	Wheat	38	26%	1085	UK, Boxworth	Bowerman and Clare (1976)
	Wheat	50	72%	2153	UK, Rothamsted	Prew and Dyke (1979)
	Barley	61	19%	540	UK, Rothamsted	Dyke and Slope (1978)
Vetch	Barley	30	23%	550	CY, Athalassa	Papastylianou (2004)
Grain legumes	Durum wheat	80	1%	72	IT, Sicily	Giambalvo et al. (2004)
Oilseed rape	Wheat	20-90	9%	490	AT, Lower	Dachler and Köchl (2003)
High fertilization (>100 kg N ha⁻¹)						
Pea	Wheat	195	22%	1608	DE, Bavaria	Panse et al. (1994)
	Wheat	190-240	22%	1600	UK, Rothamsted	McEwen et al. (1989)
	Rye	90-140	5%	500	CH, Changins	Charles and Vuilloud (2001)
Faba bean	Barley	122	14%	425	UK, Rothamsted	Dyke and Slope (1978)
	Wheat	195	23%	1528	DE, Bavaria	Panse et al. (1994)
	Wheat	150	5%	275	UK, Boxworth	Bowerman and Clare (1976)
	Wheat	170	2%	153	DE, Soest	Luetke-Entrup et al. (2006)
	Wheat	50-150	63%	1310	ES, Andalucia	López-Bellido and López-Bellido 2001
Narrow-leafed lupin	Wheat	170	42%	2753	DE, Gülzow	Luetke-Entrup et al. (2006)
Chickpea	Wheat	50-150	44%	915	ES, Andalucia	López-Bellido and López-Bellido 2001
Oilseed rape	Wheat	>100	3%	197	AT, Lower	Dachler and Köchl (2003)

4.3 Nitrate leaching

The nitrogen-rich nature of legumes and their residues has its drawbacks, including the potential for nitrate leaching and nitrous oxide emission. Leaching losses are influenced by a series of factors including the amount of available nitrate in soil, the volume of drainage water, soil texture and soil structure. To minimize losses, management aims to maximize the efficiency with which N mineralized in the soil or added in fertilizers is used by crops or retained in soils during drainage periods. In designing systems that produce grain legumes efficiently, it is important to consider both the effect of the individual species and the overall rotational system. A strong positive correlation was found between the proportion of pea in rotations and the concentration of nitrate in drainage and soil water (Beaudoin et al., 2005). This effect was also found by Plaza-Bonilla et al. (2015) where cumulative N leaching increased with the number of grain legumes in the rotation (from 1 to 3 crops) without cover crops. With cover crops, N leaching was reduced (Plaza-Bonilla et al., 2015).

The risk of nitrate leaching from intercrops is lower than from sole-crop grain legumes because of the uptake of mineral N by the non-legume component (Hauggard-Nielsen et al., 2003; Pappa et al., 2012; Mariotti et al., 2015). Deep-rooting legumes such as lupins can reduce leaching of nitrate by taking it up from deep soil layers (Dunbabin et al., 2003). In some low fertility environments such as in the Mediterranean region (Skoufogianni et al., 2013; Tosti et al., 2014) or organic systems (Möller et al., 2008), it may be advantageous to use grain legumes as cover crops to provide additional N to following crops, although there is a need to assess the associated financial costs and nitrate leaching risk. Mixtures of grain legumes with non-legumes are as effective as sole crops and more effective than bare fallow in preventing leaching, but more beneficial in providing N to the following crop (Tosti et al., 2014; Tribouillois et al., 2016). Tribouillois et al. (2016) suggested that the mixture can be designed to strike an appropriate balance between prevention of leaching and supplying N to the following crop, depending on the fertility of the site and through-flow of drainage water.

The greatest risk of leaching loss from legume-supported rotations exists between the harvest of the legume and the main growth period of the following crop. The concentration of inorganic N is usually higher after a grain legume than after a cereal grown in the same conditions (Fustec et al., 2010). Residue quality is an important determinant of timing as well as quantity of N released into leachable forms, and is affected by the species (Kayser et al., 2010; Jeuffroy et al., 2013; Li et al., 2015), cultivar (Pappa et al., 2011) and management conditions (Jeuffroy et al., 2013). The incorporation of N-rich legume residues compared to more C-rich residues such as those of cereals causes different chronological patterns in microbial activity stimulated by the presence of easily decomposable materials (Carranca et al., 2009). Inorganic N left in the profile from the preceding crop and N mineralized from legume crop residues make an important contribution to the pre-crop effect. However, the amount of mineralized N from crop residues that leaches

depends on the balance between crop uptake and drainage through the soil profile, often referred to as a “lack of synchrony” between supply and demand. The amount of nitrogen left in the soil after harvest is greater after a sole crop than after an intercrop (Hauggaard-Nielsen et al., 2003; Schmidtke et al., 2004; Neumann et al., 2007; Pelzer et al., 2012), which is attributable to improved N scavenging by the cereal (Neumann et al., 2007). The relatively short growing period of spring-sown legumes in contrast to autumn-sown cereals can lead to longer uncropped periods and thus a higher risk of leaching than in many systems with winter cereals, especially before a subsequent spring sowing.

The risk of leaching after the harvest of grain legumes can be minimized by several strategies, including the use of catch and cover crops (e.g. Justus and Köpke, 1995; Möller and Reents, 2009; Tuulos et al. 2014), and prompt autumn sowing of crops such as oilseed rape after the legume to utilize N as it is released from residue of the previous crop. Catch crops can be stubble-seeded or under-sown in the grain legume crop, and take up nitrate and other nutrients until they are frost-killed or tilled. Utilising a catch crop before spring-sown grain legumes can reduce leaching loss compared with a winter sown grain legume (Nemecek et al., 2008). Losses from the following crop are likely to be lower if N fertilizer is reduced to compensate for N available from the legume residue. Because of the interactions between crops and cover crops, and the different management options that affect leaching, assessments should take the entire crop sequence into account. Reckling et al. (2016b) proposed a simple and static framework that supports such an assessment at the systems level. In five case studies across Europe, they found that when grain legumes were introduced into arable rotations, there was a minor difference in leaching ranging from -7 to +1 kg ha⁻¹ on average compared to rotations without legumes (Reckling et al., 2016a).

4.4 Nitrous oxide emissions

Nitrous oxide (N₂O) is a powerful greenhouse gas with an effect estimated at 265 times that of CO₂ on a 100-year basis, and agriculture is a major source of anthropogenic N₂O emissions (Myhre et al., 2013). The emission of N₂O from arable crops depends on soil N status, applied N fertilizer or manure, and their interaction with crop management such as tillage and environmental factors (Henault et al., 2012; Rees et al., 2013). Soil type is also important as it is a major determinant of population compositions of denitrifying microbes (Graf et al., 2016). Losses occur both during the production of the crop and afterwards, the amount of the latter depending on residue management and whether the soil is left bare or a cover crop is sown.

Nitrous oxide emissions from grain legumes are generally lower than those from N-fertilized crops and pastures (Rochette and Janzen, 2005; Dusenbury et al., 2008), with N₂O-N emission averaging 1.29 kg/ha from legumes and 3.22 kg /ha from non-legumes (Jensen et al., 2012).

Jeuffroy et al. (2013) found that legume crops in France emitted around five to seven times less GHG per unit area than other crops. Besides differences in rates of N inputs, climates, soils and management conditions, differences between legume species and even cultivars contribute to the variability (Pappa et al., 2011).

Nitrous oxide emissions may be higher in the period after harvest of the grain legume than during its growth. The N-rich legume residues returned to the soil provide a readily available substrate for conversion to nitrous oxide as well as for leaching. The N₂O emission resulting from the residues of grain legumes is sometimes similar to that of non-legumes (Pappa et al., 2011; Jeuffroy et al., 2013) and sometimes higher (Frimpong et al., 2011), illustrating the importance of measuring emission over a whole rotation instead of just one year (Dusenbury et al., 2008; Reckling et al., 2016a). The key to reducing losses at this point in a rotation, as for prevention of leaching, is improved synchrony between crop demand and nitrogen supply, and catch or cover crops may be important. The choice of legume and the management of the residues from that crop have knock-on consequences for the N₂O emissions from subsequent crops (Pappa et al., 2011; Jeuffroy et al., 2013).

Nitrification of ammonia released from fertilizer or from mineralization of organic compounds produces nitrate, which is a prerequisite for denitrification. Nitrate is converted to nitrite by nitrate reductases and the nitrite formed can undergo a variety of reactions, of which conversion to nitric oxide (NO) by nitrite reductases (encoded by nir genes), is the best known and probably occurs most frequently in arable soils (Canfield et al., 2010). Nitrous oxide reductase (norB) reduces the NO further to N₂O, which is either released to the atmosphere or further reduced to N₂ gas by nosZ-encoded enzymes. Some bacteria possess a full set of denitrification genes, whereas others only have some (Jones et al., 2014). A field test of nosZ-carrying *Bradyrhizobium japonicum* strains on soybean in Japan demonstrated the potential to reduce nitrous oxide emission in this way (Itakura et al., 2013).

4.5 Agro-biodiversity and climate change adaptation

Increasing grain legume production generally increases the diversity of crops in arable rotations in both temporal and spatial ways. This diversification affects the associated diversity of wild flora, fauna, and soil microbes (Collette et al., 2011) along with the weed-, pest- and disease-related issues that are a component of the break-crop effect described above. Where legumes are spring-sown, they have the potential to diversify winter-crop dominated arable systems: winter crops cover 59% of arable land in Germany and 62% in England and Wales, with proportions above 70% in some countries or regions (calculated from Statistik Austria, 2010,

Defra and AHDB, 2012, Agreste, 2013 and Bundesministerium für Ernährung und Landwirtschaft, 2013).

Climate change provides an opportunity to develop the use of rarely grown crops, such as lentil in southern Germany (Gruber et al., 2012), chickpea in Central Europe (Neugschwandtner et al., 2014), narrow-leaved lupin in the Nordic region (Stoddard et al., 2009), and soybean in central Europe (Zimmer et al., 2016).

4.6 Environmental effects in product life cycles

Life-cycle assessment is a tool to examine the environmental impacts of a change by separating them into components and analysing them through an entire cycle of production and use.

Several LCA studies have analysed environmental impacts of the introduction of legumes into crop rotations. The main effects are:

- Reduction of N fertilizer use, due to minimal use of N fertilization in the legume crops and reduced fertilization of the following crop, so N emissions after fertilizer are reduced, in particular N_2O , NH_3 , NO_3 and NO_x . Furthermore, N fertilizer manufacturing is associated with consumption of fossil fuel and emission of GHGs, mainly N_2O and CO_2 , and there are costs for transporting and spreading the fertilizer;
- Potentially increased leaching after legume crops (see 4.3), countering the above-mentioned reductions of N use;
- Diversification of the crop rotation, which results in breaking pathogen cycles, potentially increased yields, possibly reduced pesticide inputs, and potentially higher associated biodiversity; and
- The environmental impacts of other feed compounds, feed additives, and feed transport, in studies at the level of livestock production.

The concrete effects depend on several factors such as the intensity of the production system (in particular the level of N fertilization and yields) and the diversity of the rotation. Nemecek et al. (2008) reported that pea grown in Germany had lower non-renewable energy requirements, GHG releases and eutrophication potential than cereals on a per hectare basis. The advantages were highest in crop rotations with high N input and a high share of cereals and less marked in diversified and less intensive ones. Adding pea to a non-legume rotation in three regions in France resulted in lower energy use and GHG releases (Nemecek et al., 2015). This advantage is eliminated when comparisons are made with 'non-legume' cropping systems designed to conserve resources, showing that the environmental and resource efficiency of the un-altered system is crucial to the outcome of increasing legume use. For example, Knudsen et al. (2014) showed that for rotations that used slurry as a major source of nutrients and for systems with no external inputs, faba bean resulted in higher GHG emissions per hectare than spring barley,

whereas winter wheat had lower GHG emissions than the faba bean for the conventional and no inputs cropping at two of three locations. Thus, the results for cropping systems were greatly affected by the performance of the crop being replaced.

More examples are available from outside Europe. Incorporating narrow-leaved lupin in a two year cropping rotation in the semi-arid environment of Western Australia decreased measured GHG emissions from wheat production by 56% per hectare, and 35% per tonne of wheat, primarily by lowering nitrogen fertilizer inputs (Barton et al., 2014). Nevertheless, the profitability of the system with the legume was lower because of the narrow range of markets for the lupin crop. When pea or lentil replaced one of the spring wheat crops in an oilseed rape - spring wheat - spring wheat - spring wheat rotation, negative environmental impacts on global warming, resource use, ecosystem quality, and human health were all reduced and economic benefits accrued as a result of lower N fertilization and higher yields (MacWilliam et al., 2014). In south-eastern Australia, total GHG emissions (CO₂-equivalent) were 225 kg t⁻¹ of grain for a 3 t ha⁻¹ wheat crop following wheat, compared with 199 and 172 kg t⁻¹ following oilseed rape and pea, respectively (Brock et al., 2016).

In France, unfertilized intercrops of wheat and pea had a lower impact on climate change, acidification, terrestrial ecotoxicity, and cumulative energy demand than N-fertilized sole crop wheat and unfertilized sole crop pea (Naudin et al., 2014). The results for the individual crops strongly depended on the allocation or system expansion method applied to handle the multifunctionality of the system.

As mentioned above, the diversification of the crop rotation leads to the expectation of lower toxicity potentials, but the high usage of biocides, especially insecticides, in conventional grain legume production (Kirkegaard et al., 2008) countered this benefit, such that the terrestrial ecotoxicity potential was not reduced (Nemecek et al., 2008 & 2015). Cederberg and Flysjö (2004) calculated for an environmentally optimized pork production farm, that in total the application of biocides could be reduced by 58% per kg of pork, of which 10% was due to reduced soy imports and 48 % was due partly to diversified crop rotation and partly to mechanical weed control instead of herbicides.

LCA of these changes in cropping system, like that of the use of grain legumes instead of imported soybean in feed chains, delivers equivocal answers because of the diversity of climates and cropping changes.

4.7 Biodiversity

Agricultural intensification in Europe over the last half century has led to biodiversity losses and population decline wild species associated with agricultural habitats (Donald et al., 2001; Benton et al., 2003). Spring sowing of legumes provides an opportunity for retaining crop stubble through winter before spring seeding. Over-wintered stubble provides combined forage and cover for small mammals, birds and insects that is not found in low-growing winter cereal crops (Potts, 2003; Evans et al., 2004; Gillings et al., 2005). In comparison to autumn-sown crops, spring-sown crops support greater abundance and diversity of weeds and arthropods, thereby providing more food to ground-foraging farmland birds (Berg et al., 2002; Dicks et al., 2013). Some of these effects may also apply to spring-sown grain legumes, but this depends on weed management. The introduction of even small areas of grain legumes into regions such as the Iberian peninsula could help the recovery of bird populations that have declined due to the simplification of farming landscapes (Cardador et al., 2015).

Legumes represent one of the highest quality foraging resources for pollinators (Jennersten, 1984; Decourtye et al., 2010). By providing nectar and pollen, the mass-flowering of grain legumes contributes to the maintenance of populations of wild and domesticated bees (Westphal et al. 2003). Faba bean flowers provide nectar to bumblebees with a long proboscis, such as *Bombus hortorum* L., *B. pascuorum* Scopoli and *B. ruderatus* Fabricius, and other large-bodied wild bees such as *Eucera numida* Lepeletier (Stoddard and Bond, 1987; Palmer et al., 2009). Faba bean and lupin flowers are important sources of pollen that honeybees (*Apis mellifera* L.) use for feeding the brood, although there is little or nectar in lupins and that of faba bean is out of reach of honeybees unless the flowers have been robbed by short-proboscis bumblebees (Green et al., 1980; Stoddard and Bond, 1987). Crop fields themselves are not suitable for ground-nesting wild bees, due to regular soil disturbance, application of biocides and the dense shading of the soil surface (Jeanneret et al., 2006).

Increases in population size and diversity of decomposer invertebrates such as earthworms and Collembola have been noted under perennial forage legumes (Eisenhauer et al., 2009, Sabais et al., 2011) but there is less information on the effects of grain legumes on them. Since soil disturbance reduces populations of many earthworm species, it is necessary to compare zero-tillage systems with and without legumes in order to detect an effect of crop diversity on earthworm populations. One such study in the United States found substantially larger earthworm (*Aporrectodea trapezoides* Dugès) numbers in a no-till soybean-maize rotation than in the corresponding wheat-maize rotation (Hubbard et al., 1999), confirming that the effect on earthworms applies in annual as well as perennial cropping systems.

Below-ground biodiversity, including bacteria, archaea and fungi, provides ecosystem services such as nutrient cycling, biodiversity resources and water quality regulation (Mikkonen, 2012).

Understanding how grain legumes influence soil microbial communities could help to understand and ultimately manipulate the break-crop effect. Pea monoculture in Alberta, Canada negatively affected a number of indicators of soil microbial function including microbial biomass carbon and bacterial diversity, in comparison with a wheat – wheat – pea rotation (Lupwayi et al., 2012). The lower microbial biomass may relate to the smaller return of residues from the grain legume compared to other crops in rotation. Scalise et al. (2015) observed shifts in bacterial community structure during legume-barley intercropping in southern Italy. The stimulated microbiota increased N cycling, leading to an increase in N release for the succeeding durum wheat crop, reducing the requirement for mineral N fertilizer.

Inoculation with rhizobium aimed at enhancing BNF may also influence yield and improve health of other crops in the rotation as a result of stimulating microbial diversity and activity. This has been observed in potato following rhizobial inoculation of preceding legume crops in Tunisia, although the effect was inoculum specific (Trabelsi et al., 2012). Incorporated legume crop residues influence the microbial community in following crops, and the effect is species-dependent. Lupwayi and Soon (2016) found greater increases in soil microbial carbon and β glucosidase activity from faba bean than from pea in Alberta. They also observed differences up to 3 years after the incorporation of legume residues indicating the importance of looking for pre-crop effects across the whole rotation.

Research comparing the impact of grain legumes with cereals on soil bacterial communities suggests that soil type, environment (Scalise et al., 2015) and management (Tautges et al., 2016) may have more impact than crop type. A meta-analysis showed a clear effect of crop diversity on both microbial richness and diversity, but there was no consistent effect of legumes on either of these parameters (Venter et al., 2016).

5 Status of legumes in Europe

5.1 Changes in EU production of grain legumes over time

The area of grain legumes in Europe declined almost continuously over the last five decades, from 5.8 million ha in 1961 (4.7% of the arable area) when recording began to 2.0 million ha in 2014 (1.6% of the arable area) (FAOstat, 2016). A major underlying driver behind the reduction in the proportion of arable land used for legume crops is the increased comparative advantage in the production of starch-rich cereals in Europe over the production of protein-rich grain legumes. Between the 1970s and the 1990s, wheat yields in north-western Europe increased annually by about 0.15 t/ha (Supit, 1997). Expansion of wheat production in Europe has been facilitated by the availability of nitrogen fertilizers, genetic improvement, irrigation and pesticides (Gervois et

al., 2008). Wheat yields have risen markedly in Europe over the last 50 years, as shown by French wheat (Figure 2). Yields of protein crops, exemplified by French pea, lag a long way behind, so these crops have become increasingly unattractive to the farmer. In the USA, however, yields of small-grain cereals and protein crops have remained similar. Pea yields have shown an overall decline in France in recent years as the increased frequency of production in the rotation led to disease and a consequent shift of production to poorer soils and associated lower yields (Magrini et al., 2016). The comparative advantage of using European land to grow wheat instead of protein crops has thus steadily increased. Specialization and intensification effects have resulted in the development of more concentrated production and more specialized farming systems in Europe during this period (Brouwer, 2006). The production of grain legumes is unevenly distributed across Europe (Figure 3) and many areas that have a large number of livestock farms have low areas of grain legume production because they are unsuited to arable agriculture. The combination of availability and low costs of synthetic nitrogen fertilizers relative to farm product prices (e.g. cereals, milk, beef) and imported protein feed has been another major enabler of this process. However, as fertilizer prices rise relative to product prices, farmers will use less fertilizer (Piesse and Thirtle, 2009), possibly encouraging legume production.

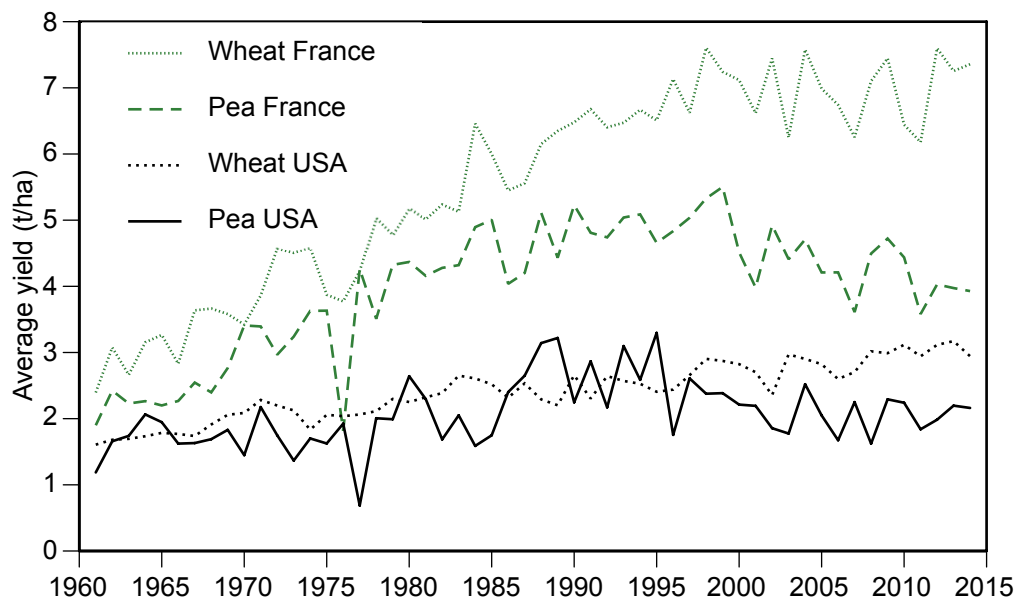


Figure 2 Yields of wheat and pea in the USA and France (1961-2014). Data from FAOstat (2016).

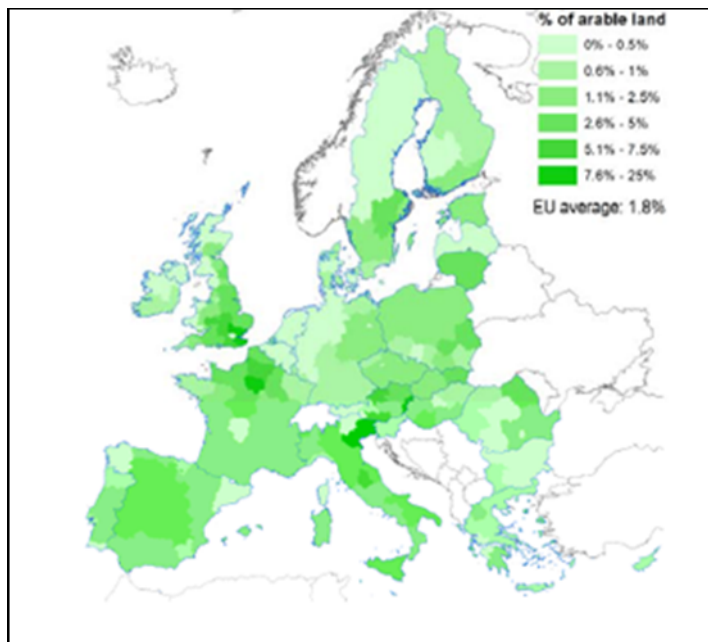


Figure 3 Proportion of EU-27 arable land used for protein crops in 2010 (%) Source: Calculations based on data from Eurostat (2013).

The area and quantity of grain legumes grown in the EU-27 countries are shown in Figure 4, which also shows the introduction (1974, 1978, 1989) of various policy support measures in Europe, along with the reduction (1992) and removal (2005-2006) of direct support. This illustrates the lack of success of those support mechanisms in significantly increasing the land area under grain legume production. It is only for faba bean, soybean and pea that an increase in the production area can be observed due to legume production moving to more fertile soils and more intensive management, (Fig. 4B). However, the production of grain legumes in Europe has increased by nearly 70% in 2015 to 2.7 million ha (Eurostat, 2016). The use of grain legumes in organic cropping systems (12% of the organic arable area) accounts for about 12% of the total grain legume area (estimated from European Commission, 2013). From these estimates it seems that the decline in production has stopped. The increase in 2015 was highest in countries with higher coupled payments (e.g. Poland), but it was also recorded in other countries (e.g. Germany, UK). The grain legume area in Germany increased from 75 thousand ha in 2013 to 188 thousand ha in 2016 (DESTATIS, 2016). It is clear from the European Commission's review of Greening (European Commission, 2016) that the use of nitrogen-fixing crops (i.e., legumes) to fulfil the ecological focus area has accounted for a significant proportion of the expansion.

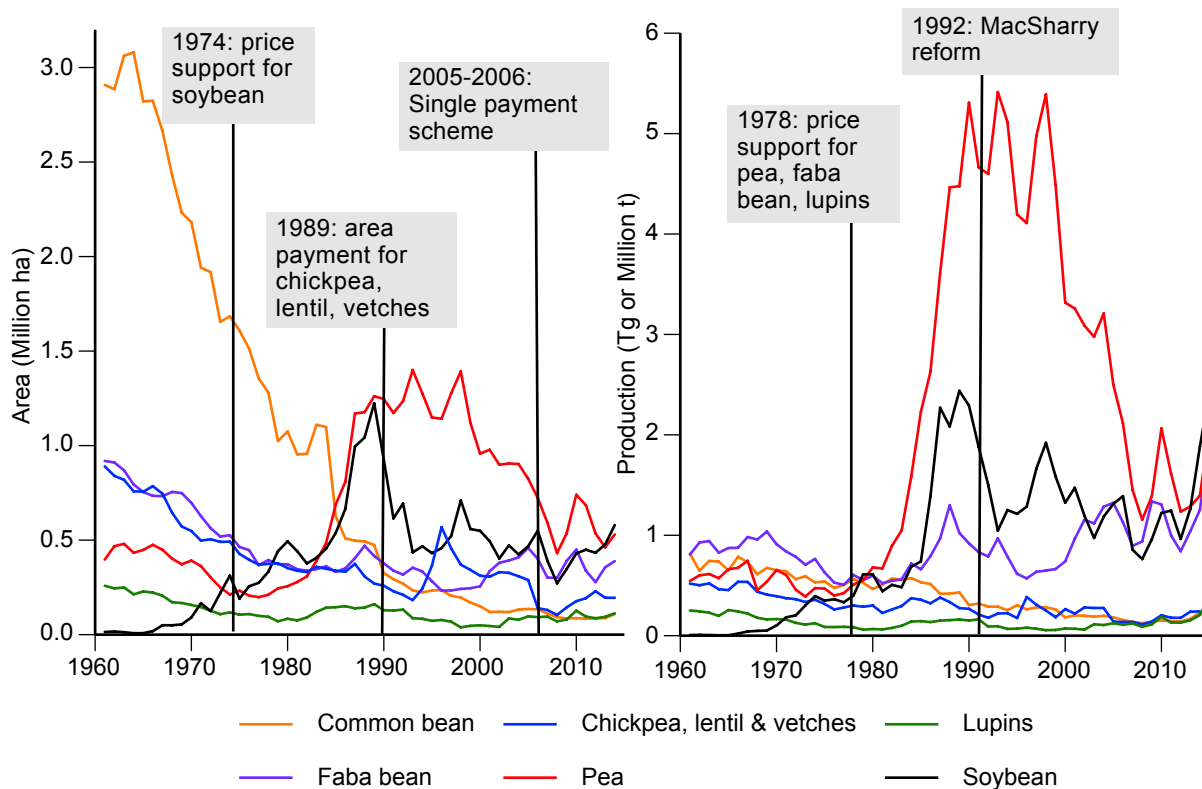


Figure 4. A, Production areas and B, production quantities of grain legume crops in the EU-27 countries (1961-2015). Data from FAOstat (common bean, chickpea, lentil and vetches) and Eurostat (all others), 2016.

While the legume cropped area declined, the proportion destined for food use reduced. In 1961, grain legume production in Europe was dominated (67% total area) by production for human consumption (exclusive food pulses: chickpea, cowpea (*Vigna unguiculata* (L.) Walp.), groundnut (*Arachis hypogaea* L.), lentil, and common bean). This dropped to 27% of the area by 2013 (FAOstat 2016). Currently, 11-15% of pea and 9-14% of faba bean produced are used for human consumption (PROLEA 2011), and only 43% of the food legumes consumed in Europe are produced within the EU (FAOstat 2016). Pea and soybean for animal feed became the two most widely grown protein crops in the 1980s following the introduction of policy support for protein feed crops, but pea production fell again two decades later (Figure 4B).

5.2 Lessons for European producers from other developed regions

In order to see what can be achieved with legumes in developed countries, we will consider two contrasting cases, Australia and Canada, where grain legumes have in many recent years exceeded 10% of the arable land sown to annual crops. Australia provides a model for southern Europe, and Canada for northern.

In the arable zone of southern Australia, until the 1970s, the primary "rotation" was wheat – sheep, with the livestock grazing the stubble and whatever pasture grew or was sown in the

fallow year. From the 1930s, subterranean clover (*Trifolium subterraneum* L.) and annual medics (*Medicago* spp.) were increasingly widely sown, often established by undersowing the wheat, thus providing a managed pasture for grazing after harvesting the cereal. When the price of both wheat and wool dropped, diversification was necessary. In Western Australia, lupins were seen as suitable crops for the prevailing acid, sandy soils already in the early 1900s, and John Gladstones led the domestication of narrow-leafed lupin from the late 1950s. From 1992 to 2002, narrow-leafed lupin was annually harvested from over 1 million ha (Figure 5A), but then areas fell, partly because the rotation (wheat - narrow-leafed lupin) was too narrow and the combination of low feed prices, soil acidification and the development of herbicide-resistant ryegrass led to the need for new management methods. New cultivars with resistance to other classes of herbicides are expected to restore the area of the crop. The primary market for lupin grains is as a feed supplement for ruminants, with some use for monogastrics and a little for fish. Flour, protein and fibre extracts are used as food supplements, and various positive effects on consumer health have been shown for the human consumer (Johnson et al., 2006; Lee et al., 2009), but market diversification is needed.

In south-eastern Australia, soils were found to be more suitable for starchy legumes. Both faba bean and pea arrived with the first European settlers in 1788 (Worgan, 1788). By the 1960s, dry pea was grown on 20 000 – 25 000 ha, and its area hit 300 000 ha in 1986 (Figure 5A). Faba bean areas first exceeded 10 000 ha in 1976 and 100 000 ha in 1997, while lentil reached the same thresholds in 1996 and 2004, and chickpea in 1983 and 1990. The food-quality, export market is vital for the market value of these crops, with the high value of chickpea crops helping to compensate for their yield variability (Schilizzi and Kingwell, 1999). Crop breeding programmes were initially scattered across the relevant states, but during the 1990s, they were reorganized, mostly into a single centre for each crop (e.g., Adelaide, South Australia for faba bean in the winter-rainfall zone) with 1-2 "nodes" for different climatic zones (Narrabri, New South Wales for faba bean in the summer-rainfall zone). In this way, the application of breeding technologies was focused, while selection for adaptation to the major climatic zones, with their different disease and stress pressures, was separated. Diversification of Australian cropping systems is seen as helping to protect the farmer against swings in commodity prices (Connor, 2004).

In Canada, the portfolio of legume species is different. Initially, soybean was restricted to southern parts of the province of Ontario, but since 2000 up to a third of the crop has been harvested from other provinces, as cultivars have been developed with earlier maturity and adaptation to longer photoperiods. Common bean is also sown in the southern parts of the country. Breeding programmes for the food legumes pea, lentil and chickpea were established at the University of Saskatchewan in the late 1970s and 1980s and became highly successful, with

most of the world's trade in lentil and pea (Zentner et al., 2002) being based on Saskatchewan produce. In 2015, 10% of the arable area of the province of Saskatchewan was sown to lentil and another 10% to other grain legumes (A. Vandenberg, pers. comm., June 2015). Production of lentil has exceeded 1 million t most years since 2004, and pea has exceeded that value since 1994 (Figure 5B). Clearly, the crops are highly successful, and important in the crop rotations of the prairie provinces. The breeding programmes release cultivars for various market classes of size, colour and composition, in addition to adaptation to different lengths of growing season and soil types. The main target is food use with its high value, and only material rejected from the food sector is relegated to the feed chain.

Both of these cases have used a combination of feed (soybean and lupin) and food (lentil and chickpea in particular) crops, and provide materials for export as well as home use. Public-sector investment in pulse breeding has been supported by small levies on production, leading to continuous breeding improvements in yield, quality and resistance to biotic and abiotic stresses. Perhaps Europe's policy-makers can learn from this.

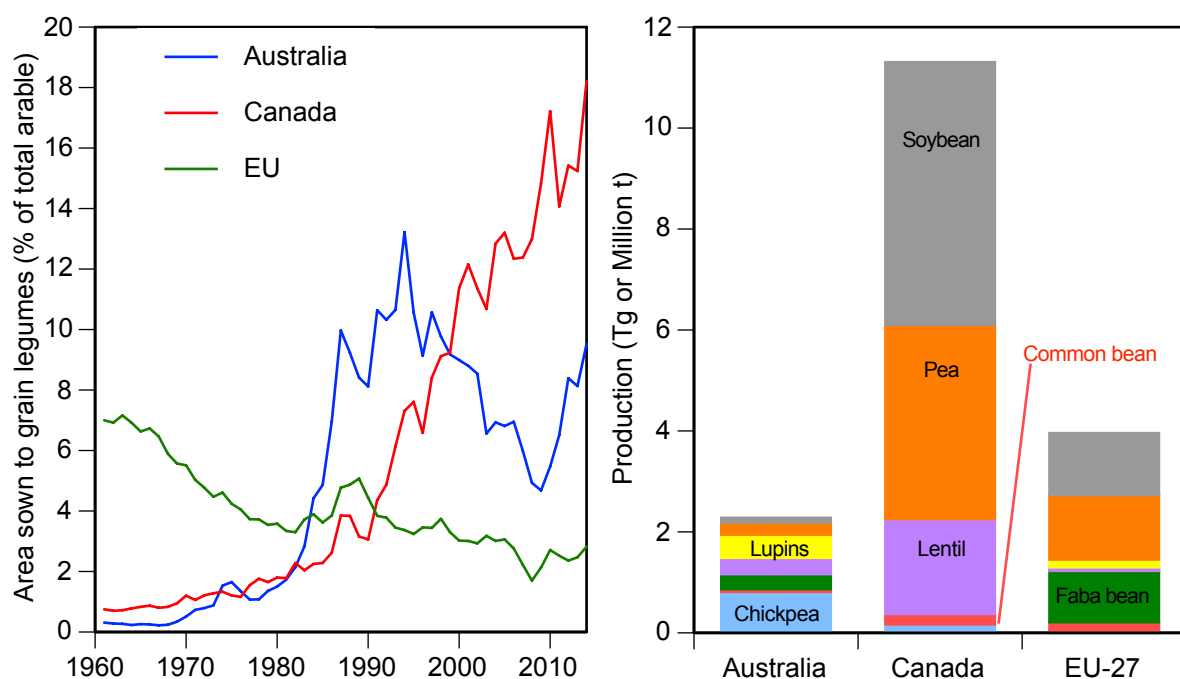


Figure 5. A. Areas sown to the major grain legumes (chickpea, common bean, faba bean, lentil, lupins, pea and soybean) as a percentage of total arable area (cereals, grain legumes, oilseeds, fibre crops, and root and tuber crops) for the EU-27, Australia and Canada from 1961 to 2015. B. Production of the major grain legumes in Australia, Canada and the EU-27 in 2013. Data from FAOstat (2016) and Eurostat (2016).

6 Developing legume production systems for Europe

Grain legumes can be produced as dry grain, green forage, silage, or green manure depending on the pedo-climatic conditions and farming system. In some parts of Europe where winters are not severe, autumn-sown grain legumes can be grown. In Mediterranean regions, grain legumes such as pea are grown as a cool-season crop harvested before summer drought or before planting an irrigated, warm-season crop such as maize. Grain legumes have generally been produced as sole crops, but there has been a resurgence of interest in intercropping (Malézieux et al., 2009). Cereal-legume intercrops can be used for forage or grain depending on growing conditions and farm management, and using them for whole crop silage is a way of boosting the forage protein content of livestock diets (Anil et al., 1998). In a recent study (Bedoussac et al., 2015), cereal-legume intercrops had a higher and more stable gross margin than the mean of partner crops grown as sole crops (702 versus 577 €/ha) under the same conditions. There is also some interest in intercropping legumes with oil crops, such as pea with linseed (*Linum usitatissimum* L.) (Zajac et al., 2013) or faba bean with either safflower (*Carthamus tinctorius* L.) or mustard (*Sinapis alba* L.) (Schröder and Köpke, 2012).

Mixing cultivars in the same field can also have advantages such as increased yield stability and disease management (Wolfe, 1985). In China, natural enemies have been shown to increase in soybean production by mixing cultivars, which means that the mixtures provide pest control benefits compared with the production of a single cultivar (Pan and Qin, 2014). Faba bean cultivars are often composed of 2-3 inbred lines that are allowed to cross-pollinate for 2-3 generations during the multiplication of seed, thus gaining some hybrid vigour as well as presenting heterogeneity to pests and pathogens (Link, 2006).

6.1 Yield stability in grain legumes

Grain legume yields are considered to be more variable than those of cereals, and yield fluctuations are one of the main reasons farmers give for not growing these crops (von Richthofen et al., 2006a). However, little and contradictory quantitative evidence is available on yield stability in grain legumes. Some statistical analyses suggest that the yield stability of grain legumes is higher than that of other crops (Schäfer, 2003; Peltonen-Sainio and Niemi, 2012), whereas others indicate the lowest yield stability for grain legumes across Europe and the Americas (Cernay et al., 2015). In a set of 14 studies, pea was the most variable in 4, lupin in 4, rapeseed in 4, and small-grain cereals in two (Table 3), indicating that broad-leaved crops indeed have more unstable yields than cereals. However, statistical analyses of yield stability using the coefficient of variation have several weaknesses. Few of the available datasets are spatially explicit, and grain legumes that are often grown on less productive soils were compared

with crops grown on all types of soils, which would negatively influence yield variation statistics. Hence, other stability parameters are needed (Döring et al., 2015).

Analysis of grain legume yield stability under the same soil and management conditions is required, e.g., using long-term cropping system experiments across a wide range of soil types. Such analyses are still rare. The yield stability of narrow-leaved lupin and pea in an organic monitoring experiment in northeastern Germany was higher than that of maize and cereals (Reckling et al., 2015). Other reasons for yield instability in grain legumes include their indeterminate growth habit, allowing them to respond to good conditions, and the relative lack of investment in breeding for stress resistance, allowing the crop to fail in poor conditions (Stoddard et al., 2009). The stress tolerance of the rhizobium symbiont often does not match that of the legume host, adding to the depression of plant growth in poor conditions (Zahran, 1999). Strategies regarding breeding and agronomic techniques need to be developed to reduce yield variability.

Table 3. Coefficient of variation (%)^a of grain legume yields compared to other crop species

Source and details	Site	Pea	Faba bean	Lupin	Common bean	Soybean	Vetch	Chickpea	Rapeseed	Wheat	Maize	Rye	Oat	Barley
Reckling et al. (2015), data set 1	Germany			46						33	14	31		
Reckling et al. (2015), data set 2	Germany	83								29	44	18	43	
Schäfer (2003), 20 yrs national yield data	Germany	9.4	10						13.8	6.9		14.4		8.5
	Denmark	9							11.6	3.8				
	Finland	17.4							12.5	13.7				
Peltonen-Sainio and Niemi (2012), National yield (5-yr moving average), 1997-2007	France	10.3							10.2	6.8				
	Germany	11.5							12.7	6.8				
	Spain	17.5							21.6	19				
	Sweden	10.2							8.4	4.7				
Peltonen-Sainio and Niemi (2012), Southern Finland, 2000-2011	Finland	7	7						13					5
	Eastern Europe	17		23	17	14	20			11		9	9	12
Adapted from Cernay et al. (2015) ^b	Northern Europe	11	15	39	20		16		7	6			8	7
	Southern Europe		8		11	13	12	17		7	8		11	16
	Western Europe	9	10	28	11	11			8	6	8	10		6

^a The coefficient of variation is defined as the standard deviation divided by the arithmetic mean; values in bold are those with the highest yield variation in the row

^b Data shown for local polynomial ('loess') regression method; other data not shown: Potato 8% in Eastern Europe, and 7% in Northern Europe, sunflower 13% in Southern Europe

6.2 Yield and quality in crop mixtures

Yields of cereal-legume intercrops vary depending on species and cultivar of both components (Rauber et al., 2001; Lauk and Lauk, 2008; Lithourgidis et al., 2011), cereal to legume ratio (Hauggaard-Nielsen et al., 2003, 2006, 2008, 2009; Micek et al., 2012) and growing conditions (Hauggaard-Nielsen et al., 2009). The yield advantage of intercrops or crop mixtures is generally attributed to complementarity of resource interception and use, but may also result from interspecific facilitation or the positive influence of one species on another (Willey, 1979; Vandermeer, 1989; Malézieux et al., 2009; Brooker et al., 2015). The effect of intercropping is often measured by the Land Equivalent Ratio (LER), which compares the yield of the intercrop with that of the pure crops (Mead and Willey, 1980). A value above 1 indicates that the total yield of the intercrop is higher than the average yield of the components grown separately. Most published studies on intercropping focus on above-ground interactions, although changes in microbial biomass size and activity and bacterial diversity have also been found (Saini et al., 2004; Lupwayi and Kennedy, 2007; Song et al., 2007). For success, crop mixtures require complementarity rather than competition in resource interception, and the different above-ground and below-ground architectures and physiologies of cereals and grain legumes are often well suited in this way.

The advantage of cereal - legume mixtures over pure cereals is generally greater in systems with little or no usage of nitrogen fertilizer (Jensen, 1996; Ghaley et al., 2005) and agrochemicals (Szumigalski and Van Acker, 2005). A meta-analysis of the effect of N fertilizer on production in grain legume – cereal intercrops showed that it decreased the proportion of grain legume in the mixture without significantly affecting LER (Pelzer et al., 2014). Weed suppression in cereal – legume intercrops often exceeds that of sole crops, with examples from barley – pea (Corre-Hellou et al., 2011), winter wheat – faba bean (Bulson et al., 1990; Haymes and Lee, 1999), winter wheat – pea (Paolini et al., 1993), and maize – common bean (Bilalis et al., 2010). This reflects the increased resource use of intercrops, particularly light interception (Liebman and Robichaux, 1990; Corre-Hellou et al., 2011), and is shown in terms of reduced total weed biomass, weed species richness and relative abundance of dominant weeds (Poggio, 2005). Chemical weed control is difficult or impossible in intercrops, as few herbicides are tolerated by both a cereal and a legume.

In 58 field experiments conducted in France and Denmark since 2001 where either no fertilizer or organic fertilizer was applied, intercropping led to higher and more stable grain yield than the mean of the corresponding sole crops (3.3 versus 2.7 t/ha) (Bedoussac et al., 2015). Intercrops usually yield more than sole-crop legumes (Pelzer et al., 2012), and often more than sole-crop cereals (e.g. Jensen 1996; Hauggaard-Nielsen et al., 2001; Hauggaard-

Nielsen et al., 2003; Andersen et al., 2004; Naudin et al., 2010), but not always (Hauggaard-Nielsen et al., 2006; Pelzer et al., 2012; Neugschwandtner and Kaul, 2014). The proportion of legume and non-legumes in the mixture influences both yield and N offtake, and increased yield has frequently been observed with higher total seed density of mixtures compared to sole crops, such as 100% + 50% (faba bean and wheat, Bulson et al., 1997; pea and oat, Neumann et al., 2007 and 2009). The proportions of crops in the mixture can be adjusted for maximum yield according to the site and environmental conditions that influence competition (Neumann et al., 2009). In intercrops used for forage, the crude protein yield can be greater than in sole-cropped legumes, for example, a faba bean – triticale mixture yielded 12% more protein than faba bean alone (Dordas and Lithourgidis, 2011).

Cereal protein concentration was higher in unfertilized intercrops than in sole crops (11.1 versus 9.8 %) (Bedoussac et al. 2015). Intercropping with grain legumes increased the N concentration of wheat by 8% on average across a range of European sites managed organically and in some cases also increased its S concentration by 4 % on average across the same range of sites (Gooding et al., 2007). Neumann et al. (2007) found grain nitrogen content of both oats and peas were greater in mixtures than in sole crops. Lodging of peas can limit their yield (Annicchiarico and Iannucci, 2008), partly due to loss of harvestable yield and partly to reduced light penetration reducing pod formation (Schouls and Langelaan, 1994), but the cereal in an intercrop provides physical support that reduces this lodging (Podgorska-Lesiak and Sobkowicz, 2013).

Nutrition is another factor affecting the success of legume – cereal intercropping. The cereals are generally better than legumes at taking up mineral N, leaving the legume to rely on BNF, as discussed earlier. Legume root exudates liberate phosphate and several cation species, and the cereal roots liberate other nutrients, leading to increases in the P uptake of cereals and Fe and Zn uptake of legumes compared to sole crops (Li et al., 2007; Zuo and Zhang, 2009; Xue et al., 2016).

6.3 Crop protection (weeds, pest and diseases)

Due to pest and disease constraints and subsequent declines in crop yield and soil function, grain legumes are grown within rotations rather than in consecutive years. A critical component of rotation design is the use of crops with different life cycles and growth habits for control of weeds, pests and diseases (Garrison et al., 2014; Cook, 2003). The frequency of legumes within a rotation is likely to be determined by the longevity of survival of their

pathogens. Too frequent inclusion of grain legumes in the rotation reduces their yields (Pfender & Hagedorn, 1983).

Grain legumes suffer from a wide range of diseases and pests. The cool-season pulses, namely chickpea, faba bean, lentil and pea, are closely related and have closely related pathogens. Each is host to a cool-weather blight fungus in genus *Ascochyta* that spreads primarily by rain-splash and is potentially seed-borne. Pea hosts two additional fungi in its disease described as "ascochyta complex", *Mycosphaerella pinodes* (Berk. & A. Bloxam) Vesterg. and *Phoma medicaginis* var. *pinodella* Malbr. and Roum. *Botrytis cinerea* Pers., grey mold of chickpea and lentil, and *B. fabae* Sard., chocolate spot of faba bean, flourish when surfaces remain moist at temperatures near 20°C and can cause complete crop loss. Each of the cool-season pulses hosts a rust in genus *Uromyces* that is more prevalent in warmer weather conditions than the other two genera. The warm-season legumes also host rust diseases, *Uromyces* spp. on common bean and *Phakospora* spp. on soybean. Plant breeders have made progress in identifying sources of resistance to most of these leaf and stem diseases, but not to those of roots and crowns, where the most challenging is root rot of pea, caused by the oomycete *Aphanomyces euteiches* Drechsler that can remain viable in the soil for up to 9 years after a pea crop (Gaulin et al., 2007; Rubiales et al., 2015). A key part of integrated management of these diseases is to ensure that successive legume crops in rotations are sufficiently far apart in time that the inoculum has reduced and far apart in space that residues cannot spread infection (Stoddard et al., 2010). Generalist pathogenic fungi such as *Sclerotinia sclerotiorum*, *Fusarium* spp. and *Verticillium* spp. attack grain legumes when conditions are favourable. The warm-season legumes are subject to bacterial blights, whereas these are seldom found on cool-season legumes. Another problematic fungus is *Colletotrichum lupini* (Bondar) Nirenberg, Feiler & Hagedorn, the causal agent of anthracnose. In Germany, narrow-leafed lupin largely displaced white and yellow lupins in the 1990s because of its higher tolerance to this fungus.

The main insect pests of grain legumes are aphids, bruchid beetles, leaf weevils and moths. Of the aphids, *Aphis fabae* Scopoli, *A. glycines* Matsumura and *Acyrtosiphon pisum* Harris are particularly widespread and spread many viruses, so control is vital (Stoddard et al., 2010, Rubiales et al., 2015). Furthermore, *A. fabae* has a wide host range of over 200 species. Larvae of several bruchid species develop within growing seeds of the grain legumes, so they are shielded from many insecticides, and their damage greatly reduces the quality of the crop for both seed and food uses (Keneni et al., 2011). Leaf weevils in genus *Sitona* do damage to the plant in two ways: the adults cut distinctive, semi-circular notches in

the leaves and the larvae eat the root nodules, so even low rates of infestation reduce yield (Lohaus and Vidal, 2010) and pNdfa (Corre-Hellou and Crozat, 2005). The larvae of the pea moth, *Cydia nigricana* Fabricius, consume many grain legumes including faba bean, lentil and narrow-leaved lupin, but the egg-laying females are most strongly attracted by pea (Thörning et al., 2014). Seeds that are only partly damaged by the larvae are not easily separated from undamaged seeds during processing, reducing value for seed and food uses.

Weed control is seen as a major challenge for grain legume production due to their generally open growth habit and slow initial growth rate, compared to cereals. Increased crop density often helps to control weeds (vining pea, Lawson and Topham, 1984; faba bean, McEwen et al., 1988), but increases seeding costs, lodging due to the weaker stems of the crowded plants, and the spread of diseases. In both faba bean and chickpea, combinations of row spacing and mechanical control were competitive with herbicides, but in field pea some herbicide was still needed in combination with these other methods (Avola et al., 2008). The use of cultivars that are competitive against weeds is another important strategy for optimising grain legume production, especially in systems where herbicides are avoided. The improved standing power of semi-leafless pea over conventional-leaved pea comes at the cost of weed suppression in pure stands (Spies et al., 2011) and in organic crop mixtures with oat (Gronle et al., 2015).

Some legumes are affected by parasitic weeds, of which the broomrapes are the most economically damaging (Rubiales and Fernández-Aparicio, 2012). Crenate broomrape (*Orobanche crenata* Forsk) is widely distributed in the Mediterranean basin and attacks most grain legumes (Rubiales et al., 2009). The major control strategies currently available to farmers are the use of resistant cultivars and chemical control, along with appropriate rotations (Rubiales and Fernández-Aparicio, 2012). Intercropping with oat reduces the parasitism of faba bean and pea, possibly due to allelochemicals from the oat roots (Fernández-Aparicio et al., 2007).

6.4 Soil management, organic matter and soil structure

Legumes have the potential to improve soil structure, water holding capacity, increase soil organic carbon (SOC) (Leithold et al., 1997; Jensen et al., 2012), and reduce soil compaction. This effect results from the strong tap-root and thick lateral roots of grain legumes, brassicas and other broad leaved crops that contrast with the fine roots of the small-grain cereals. When the roots die and decay, they provide a continuous network of

residual root channels and macropores in the subsoil, penetrating soil hardpans (especially by species with a vigorous tap-root such as faba bean) (Rochester et al. 2001, Jensen and Hauggaard-Nielsen 2003). This enhances soil permeability and hence both water infiltration into the soil (McCallum et al., 2004) and the deep growth of the roots of the following crop (Kautz et al., 2013). Optimising production in cropping systems requires good soil structure, and pea and faba bean have been shown to be more sensitive than cereals to compaction (Lipiec and Samota, 1994; Arvidsson and Håkansson, 2014), while narrow-leafed lupin may be more tolerant than barley (Trückmann et al., 2008). Bengough and Young (1993) showed that pea root elongation was reduced as bulk density and penetration resistance increased. There are cultivar as well as species differences in sensitivity to compaction (Vocanson et al., 2006). Grain legumes contribute organic matter to soil via inputs of organic residues during growth (rhizodeposition), root turnover and nodule turnover as well as through residue incorporation.

The quantity of residues from a grain legume is likely to be less than that from a cereal as a result of lower production of both above- and below-ground biomass although comparative estimates of above and belowground biomass are hard to find in the European literature. The impact on soil organic carbon is affected by residue quality as well as quantity and legume residues generally have lower C:N ratios than non-legumes (Meyer-Aurich et al., 2006; Begum et al., 2014; Laudicina et al., 2014; Jensen et al., 2012; Sanz-Cobena et al., 2014; Tosti et al., 2014), although this varies with species and cultivar (Jeuffroy et al., 2013; Schwenke et al., 2015). In combination with their generally lower lignin content (Laudicina et al., 2014) than cereal roots, this results in more rapid decomposition.

The rapid decomposition of legume residues has important implications for designing rotations and optimising systems with grain legumes. The rotational and break-crop effects of introducing a wider variety of crops into cropping systems noted above (Section 3.3) have the potential to increase crop yield leading to increased residue biomass and hence soil carbon input (West and Post, 1992; Drury and Tan, 1995). The difference depends not only on the above- and below-ground properties of the introduced crop but also on the nature of the monoculture comparator. In a meta-analysis, mixed rotations were found to increase soil carbon by 11% compared to continuous soybean but by only 2.9% compared to continuous wheat (McDaniel et al., 2014). Introducing soybean into continuous maize caused a decrease in soil organic carbon (SOC) on account of the lower biomass and C:N ratio of the legume (Meyer-Aurich et al., 2006). Similarly, SOC accumulation was lower under wheat/faba bean rotations (3.6 t ha⁻¹ over 19 years) than in wheat monoculture (5.6 t ha⁻¹

over 19 years) (Laudicina et al., 2014). In terms of rotation design, there is also variation between species in the factors determining the impact on soil carbon, for example, vining pea residues had a significantly higher C:N ratio (28) than forage pea (20) or faba bean (17) (Lupwayi and Soon, 2016). The possibilities for improving soil carbon offered by intercrops with grain legumes as opposed to sole crops are also worthy of consideration. The increase in root density (Li et al., 2006) and root biomass (Cong et al., 2015) in intercrops compared to sole crops can lead to increases in soil carbon (Cong et al., 2015).

The impact of grain legumes on soil structure is related not only to carbon inputs but also to the soil microbial community (See Biodiversity section) and the physical impact of grain legume roots and associated mycorrhizal hyphae. The root length of a grain legume plant may be only one tenth that of a cereal plant (Hamblin & Tennant, 1987, Heeraman and Juma, 1993). Haynes and Beare (1997) suggested that since legume roots deposit material of higher N content, there is greater exploration of those aggregates by fungal hyphae, enhancing aggregate stability. Grain legume species differ in their ability to create and stabilize soil aggregates, with lupin shown to be more effective than pea in both these measures of soil structure (Chan and Heenan, 1996). This may relate to root length, architecture and/or exudation, but there is little comparative information available. Interaction with tillage is another important issue and under Mediterranean conditions, faba bean root systems have been found to respond positively to reduced tillage in terms of root length, diameter and biomass as a result of improved soil structure and increased water storage capacity (Muñoz-Romero et al., 2011).

Soil pH should be optimized for the crop along with an adequate supply of major and micronutrients for crop growth and function. One side-effect of the release of acids by legume roots is a gradual acidification of the soil, usually countered by periodic applications of lime, and partially countered by the alkalinity of the crop residues. Low soil pH can reduce the survival of rhizobium during phases of the rotations when no host plant is present (Carter et al., 1995).

6.5 Reconnecting crop and livestock production

Specialization in agriculture has been driven by a combination of policy and economics (Russelle et al., 2007; Hendrickson et al., 2008) facilitated by cheap energy. Spatial separation of livestock and feed production between continents and regions has resulted in widely acknowledged negative environmental consequences, for example, water pollution (Larsson and Granstedt, 2010) and loss of both crop diversity and biodiversity (De Fries et

al. 2004). It has also resulted in arable farming systems becoming increasingly dependent on synthetic fertilizer for nutrients and in some arable areas, levels of top soil carbon are declining (Goidts and van Wesemael, 2007; Heikkinen et al., 2013). As a result, there is an increasing interest in Europe in reconnecting crop and livestock production not just at farm but at local and even continental levels (e.g. Moraine et al., 2014; Peyraud et al., 2014). On farms that are mixed, grain legumes can be used as home-produced high-protein feed without transport costs. Often, using home-produced grain legumes is economically viable as the value of the feed exceeds the market price (Preissel et al., 2017). Nevertheless, a mass return to mixed farming systems is unlikely for many reasons, including infrastructure costs associated with livestock housing, fences and watering points, and the knowledge needs of farmers. Pairing farms or developing groups of farms that trade different commodities in a structured way within a region is perhaps a more likely outcome as a means of overcoming both production constraints and local environmental issues (Asai and Langer, 2014; Moraine et al., 2016). Arable farms can then combine the nitrogen in manure with nitrogen from BNF to reduce reliance on synthetic fertilizer and build soil organic matter within the crop rotation. Franzluebbers et al. (2011) reported increases in crop yield at the farm level as a result of manure exchange between farms. This also has the potential to reduce leaching losses by reducing the amount of manure spread per unit land area within the region. Asai et al. (2014) found in 2009 that half of all Danish farms were involved in manure exchanges. Within the EU Regulation (834/2007) for organic farming, it is stipulated that livestock feed must be grown within the region, which provides an incentive for grain legume production close to farms producing organic chicken or pork without land to produce enough protein-rich feed.

6.6 Designing grain legume production systems

Growing more grain legumes in future requires changes to the cropping system, the sequence and the management of crops. To support this transition, the design of cropping systems can utilize several approaches, including field experiments to test cropping practices on-station, on-farm experiments where farmers test new practices on their farms, and cropping system planning tools. The latter are particularly relevant to assess environmental, economic and agronomic impacts of cropping system *ex ante*. Reckling et al. (2016a) found reduced trade-offs between economic and environmental impacts when legumes were introduced and showed that economic-environmental optimized cropping systems with legumes can be designed using a simple framework. Tools such as MASC (Sadok et al., 2009) and ROTOR (Bachinger and Zander, 2007) can also be used for a

participatory process with farmers to design new systems. A combination of the different approaches to design cropping systems with legumes could promote implementation by farmers (Reckling et al., 2016c).

7 Crop improvements necessary

In order to make grain legumes into economically more attractive crops that farmers will grow, major advances in yield and yield stability need to be made and new markets need to be developed.

Pea is the most widely grown grain legume in Europe, but it suffers from poor standing ability, poor ground coverage and low competitive ability against weeds, along with relatively low protein (20-24%) and, on many soils, low productivity. Faba bean is the second in area, the first in yield per hectare, and on account of its higher protein content (28-32%), highest in protein yield, but is considered to be adapted to heavy or clay-rich soils and too sensitive to water deficit on sandy soils. For sandy, acid soils, the three agricultural lupins (white, yellow, and narrow-leafed) are well suited with deep rooting and good drought tolerance, but only white lupin achieves good ground coverage. The experience of the authors is that yellow lupin is the most drought-tolerant and suited to the sandiest soils, followed by narrow-leafed, and finally white. Both white and yellow lupin have higher protein contents (35-45%) than the starchy pulses, while that of narrow-leafed lupin is close to that of faba bean. Lentil, chickpea and common bean all have protein contents in the same range as that of pea and have relatively low yields, but high values as they are primarily food rather than feed crops. Frost tolerance is limited in soybean and unknown in common bean. The diseases of the main grain legumes have been mentioned above, and all species could use better tolerance to the full suite of abiotic stresses. Thus, there is much to be done in breeding programmes, and each programme has its own set of priorities.

In terms of the remit of this paper, we will focus on factors affecting the cost of management and the value of the product. Weed control is a major problem when growing most grain legumes. Some species are less competitive than others, owing to very open canopies (semi-leafless pea and narrow-leafed lupin are two cases in point), and since their sowing densities are an order of magnitude less than those of cereals, ground coverage is later, regardless of the speed of germination and establishment. Because of their relatively low hectarages, the grain legumes have not attracted sufficient investment in development or licensing of herbicides. Induced mutagenesis has raised the level of Metribuzin tolerance to

an acceptable value in Western Australian narrow-leaved lupin breeding (Si et al., 2009), and a similar strategy should work in other crops. Diversity of herbicides is as necessary to sustainability as biodiversity is, in order to prevent selection of herbicide-resistant weeds. The hypogeal germination habit of pea, lentil, chickpea and faba bean protects the cotyledonary buds from damage during weed-harrowing, but the corresponding growing points of the lupins, common bean and soybean are exposed to damage in this way.

Yield is the main breeding objective, and can be achieved through improved biomass production, better partitioning into seeds, and enhanced tolerance to biotic and abiotic stresses. Sources of resistance to many individual stresses have been found in germplasm of the various species and the search for other sources is continuous. Bringing those resistances into otherwise well adapted backgrounds requires investment and time, and technologies such as genome-wide association and genomic selection are in development in order to be able to identify first the gene regions conferring the enhanced traits, and then offspring carrying the desired combinations, rapidly and efficiently.

8 Forward look:

Europe's remarkable agricultural productivity can be partly attributed to specialization in high-yielding cereals and oilseeds grown using synthetic nitrogen fertilizer, well-developed supporting technology such as pesticides, and large imports of soy from North and South America for livestock feeding. However this productivity comes at a cost for the environment linked to imbalances in European cropping systems. Developing more sustainable systems is not about promoting legumes. It is about the effective rebalancing of farming and food in Europe using legumes. It is also about global change. In South America, cropping systems with more than 50% soy are common, so their cropping sequences are too simple, dominated by legumes. At the same time, enabled by imports of soy, farmers in Europe have reduced legume production to the point that most European cropping systems do not use any legumes at all. But is change really needed?

Europe is more self-sufficient in plant protein than is commonly implied. While Europe imports about 70% of the protein-rich material used for feed supplementation, it is actually about 70% self-sufficient in tradable plant protein when all grain and arable forage protein sources are considered (Murphy-Bokern et al., 2017). European farmers are as good as or better than farmers in legume-exporting countries at growing legumes, but they are especially good at growing cereals. Many economists would argue that the current situation reflects rational economic decision-making by farmers and wider economic advantage that the use of comparative advantage brings. However, we can speculate on a number of

fundamental changes that determine the likelihood of a rebalancing of agriculture supported by legumes grown in Europe. These are to do with:

1. better assessment of the economic performance of legumes;
2. yield and yield stability; the economic value of supporting services;
3. the value of the crop produce;
4. gaining a market advantage from environmental effects;
5. broad-based transition in value chains; and
6. public policy support.

Taking these in turn, we start with the understanding that the real (farm-level) economic performance of legumes is higher than conventional gross margin analysis indicates. This means realizing the full farm-level economic value is a way forward (Preissel et al., 2015; Zander et al., 2016). However, even where the economic performance of legume crops is underestimated, there is consensus that there is still a lack of compelling economic grounds for growing legumes for many farmers. This means that in most situations, the technical performance of legume crops also needs to improve compared with competing crops. There is some good evidence that this is possible. Cereal crop yields are stagnating even though breeding continues to increase yield potential (Brisson et al., 2010). If the performance of cereals stagnates or even declines, and performance of legumes continues to increase, we will over time see the attractiveness of legumes for farmers increase. This scenario is supported by investment in plant breeding and improving cropping systems in particular.

The cost of crop inputs, especially nitrogen fertilizer, will also impact on prospects. The economic value of the biologically fixed nitrogen depends ultimately on the price of synthetic nitrogen fertilizer. Similarly, the value of other aspects of the break crop effect depends on the availability and cost of pesticide-based control of weed and other problems. In an excellent example of combining biological and economic research, Humphreys et al. (2012) identified a tipping point in the ratio of fertilizer nitrogen price and the farm-gate price of milk in Ireland. The scope for this effect in arable systems is somewhat lower although clearly the attractiveness of more diverse cropping sequences increases as the cost of maintaining intensive cereal production using synthetic fertilizer nitrogen and plant protection products increases.

The relationship between the price of grain legumes and the price of the most commonly grown or competing crop product will influence cropping decisions. In Bavaria, soybean production is competitive with wheat production when the price of soy exceeds twice that of

the cereal (Schätzl and Halama, 2013). If the price of soy relative to wheat continues its rise then growing soya and other legumes will become competitive for more farmers in relevant regions. This increase in price reflects rapidly growing demand for soy from China. Using analysis of scenarios, Pilorge and Muel (2016) indicated that the current high prices for plant protein are here to stay. It is reasonable to conclude that protein will remain valuable compared with carbohydrate and oil increasing the potential for legumes in Europe with protein yield per hectare being a key determinant of success.

There is also definitely growing interest in higher process quality in the agri-food sector, particularly reduced negative environmental impacts (Murphy-Bokern and Kleeman, 2015). However, to gain from such market premiums gained through for example produce certification, it must be clear that legume crops support improved environmental performance that consumers recognize and reward. As is evident from this review, diversifying our cropping systems using legumes will bring environmental benefits, but these benefits are modest and probably not sufficient to drive large premiums.

In addition to changes in the individual fundamental factors outlined above, there is also the possibility of combinations of small changes leading to breakthroughs at the system level. Voisin et al. (2014) argued that legume production has been hindered by lock-in within incumbent structures and processes. For example, past trade agreements supported specialization in cereal production and stimulated infrastructure investment in processing large amounts of imported soybean meal. The resulting lock-in or dominance of the incumbent system is manifest for example in the market under-valuation of pea and faba bean in relation to their nutritional contribution in compound feeds. Voisin et al. (2014) argued that starting with combining niche high-value chains that give priority to a secure and high quality supply within regionalized systems, new broader structures and processes can be established. The theory of transition (Geels, 2011) indicates that such new systems can emerge when the effects of several niche innovators coincide. Eventually, new value chains, such as those exploiting food uses, may synergize with each other and with the dominant system.

Developments reviewed here have provided a rich resource of practical knowhow embedded in farming and food businesses which can now be used to improve systems. Such an open 'multi-actor' approach complements the research we have had to date, largely about components of systems. Overall, a four-fold increase in grain legume production from the 2014 level to about 6.5 million ha (6% of the arable area) would be beneficial from a farming

systems perspective. Given the huge market for plant protein now met by imports, there is no fundamental internal market constraint on this high level of growth. If we assume that the output of non-legume crops remains stable (due to rotation benefits and the general technical progress in eastern Europe), the aforementioned four-fold increase would result in an increase in the supply of protein from EU-grown grain legumes from 1.37 million tonnes of plant protein to 5.48 million tonnes. This compares with a total demand for 54 million tonnes of 'tradable' arable plant protein including a net import of 15 million tonnes of soy protein. This would reduce the deficit in high protein commodities from about 70% to about 50%. This might be regarded as a small effect, but we can conclude here that it comes with broad complementary agronomic, economic, environmental, and social impacts. Unless this change causes a reduction in cereal exports, we can expect improvement in Europe's balance of trade. Given that the proportion of grain legume crops in European organic systems is 12% on average, and frequently as high as 20%, further expansion in conventional cropping to 10% of the arable area to approach the levels sustained in Canada and Australia is a reasonable target. This would radically reduce reliance on imported soy. The challenge for the future is the optimal expansion of production of legume crops to while maximizing complementary impacts so that change can be economically, socially and politically sustained. For this, European legumes must be competitive for land at produce prices that are competitive with imports.

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